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一种自动驾驶电动汽车线束布局优化方法

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摘要：近年来，随着汽车自动驾驶、数字化、电动化技术的不断发展，汽车的功能不断增加，车辆内部线束也随之增加。由于过多的线束导致车辆自重增加的问题日益突出。为了实现能源的高效利用和出行方式的可持续性，开发人员需要通过优化线束布置来尽可能多的减轻车辆自重，同时降低成本。由于与线束相连的车辆零件位置固定，因此需要一个算法在车辆零件位置为限制条件下，优化车辆线束布局。之前的研究方法通常只考虑线束设计的部分限制因素，且没有考虑线束三维结构。在本文研究中，开发了一种新型的优化线束布局的方法，该方法考虑了与包装，温度负载以及装配难易相关的各种限制因素。该方法可以根据设计需求来控制线束布置方法，如在沿着车辆纵轴方向布置更多线束，以避免在车辆外围布置线束。通过该方法，可以高效地计算出线束长度、直径，以及精确的布线路径。

关键词：电动汽车；汽车线束；布线优化；Dijkstra算法
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A Framework for Optimizing Wiring Harness of Automated Electric Vehicles

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Abstract： Autonomous driving， digitalization， and electromobility have greatly increased the number of functions in vehicles in recent years. This trend will continue in the coming years. An extension of functions is often associated with an increase in the quantity of wires. However， for energy-efficient and thus sustainable mobility， developers need to keep the vehicle weight as low as possible. Likewise， the minimization of costs must be strived for. For this purpose， an algorithm is necessary， which designs the wiring under the specification of component positions. We took into account various constraints with regard to packaging， temperature load， and ease of assembly aspects. In addition， the routing can be controlled by desired preferences， e. g. more wires along the center of the vehicle than on the outside in the direction of the vehicle´s longitudinal axis. The specification of cable lengths， diameters as well as the exact routing are the results. Previous approaches usually consider only partial aspects， no 3D structure， and only a few number of constraints.

Key words： wiring optimization； high voltage power supply； dijkstra algorithm； vehicle packaging； electric vehicle

The number of functions and systems in vehicles has risen sharply in recent years. This is due to the transformation to electric， autonomous vehicles and the quest for more comfort and greater safety. This trend is expected to continue in the coming years. As a result， the number of components and systems in the vehicle will continue to increase. For an electric vehicle power supply system， this results in an increase in complexity in two dimensions. First， the number of components that need to be supplied with energy is increasing. Second， the introduction of additional voltage levels， e. g. ， 48 V and HV， requires additional supply levels that harmonize with the existing architecture. An optimization process can help minimize the cable length and thus its weight while respecting further packaging constraints. This leads to a higher efficiency， reduced costs， and lower space requirements， which ultimately has a positive effect on customer satisfaction. In many publications on the optimization of the vehicle power supply system， the wiring harness is not considered or is

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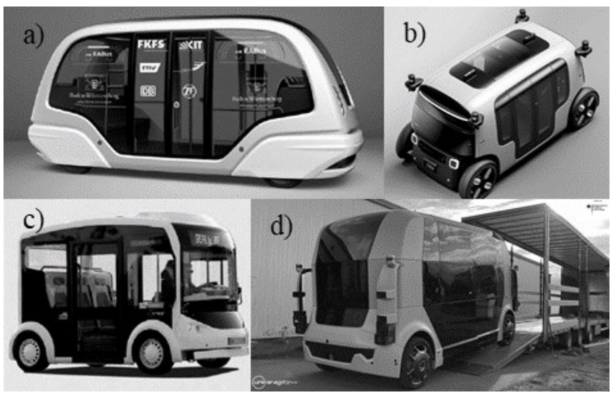
greatly simplified. This is due to its relatively small contribution to overall vehicle efficiency. However, the wiring harness makes an important contribution to the optimization of the vehicle packaging and the design of the power supply system. Packaging aspects, which are reflected in development costs, and manufacturing costs are particularly crucial. The trend toward autonomous driving leads to the development of new vehicle geometries, e. g. autonomous shuttles, which are often higher than previous vehicles for private transport. **Fig**. 1 shows four autonomous shuttle concepts, in which a) is the ZF shuttle[1], b) the Zoox shuttle[2], c) the Cristal[3], and d) the UNICARagil autoSHUTTLE[4].



a) ZF-Shuttle, b) Zoox, c) Cristal, d) UNICARagil autoSHUTTLE

Fig.1　Autonomous shuttle concepts

1　Change in electric consumers for autonomous vehicle

Packaging is becoming more important in the development of zone-based electrical/electronic (E/E) architectures, as the zones are defined geometrically. The motivation to establish a zone-based E/E architecture is to reduce cable lengths. To achieve this goal the paths of the cables must be optimized as well[5].

There are various approaches for optimizing the routing of the wiring harness in a vehicle. Three of these approaches are presented in this section.

1.1　Optimization of cable length

In Ref. [6] Masoudi reduced the length of cables using a path finding algorithm. The algorithm provided the shortest path even for paths with complicated geometries as obstacles. In Ref. [7] Masoudi extended the method to reduce the total length of all cables. This was done by simultaneously maximizing the common path of as many cables as possible. The calculation is based on Eqs. (1) and (2) with the breakouts B_1 and B_2, the starting point S, the target point G, and the number of cables n_w.

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

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

1.2　Optimization of manufacturing cost

In Ref. [8] Nackenich introduced a method to integrate 3-dimensional mock-up in the development process. He assigned additional data to the mock-up. This supported the development and production process, but the optimal cable path in the 3-dimension structures was not considered. A cost model for wire harnesses depending on the variation complexity was discussed in Ref. [9]. The model included production and material costs and aimed to reduce the levels of the wiring harness. Level designated the variants of the same wiring harness caused by the configuration options of the vehicle type. These manufacturing cost driven approaches are helpful for designing the wiring harness itself, but they are not suitable for finding the optimal routing.

1.3　Methods for system optimization

In Ref. [10] Braun reduced the vehicle to a surface of nodes and edges. The position of components was on the nodes and the connecting cables run along the edges. The number of nodes and edges was set to five in the vehicle's transverse direction and eight in the longitudinal direction. The partition was defined by the components of the chassis and interior. This provides an illustrative replica, but it is not clear how a refinement of this structure should be done. A link between the quantity of nodes and edges, the vehicle chassis, and the interior components cannot be justified by the real distribution of consumers in the vehicle. A flexible definition of the number of nodes and edges offers the possibility of adapting to the granularity.

Depending on the vehicle dimensions, an optimum can be selected from the exact position reproduction of the consumers and computing time. In addition, the progress in electromobility has led to the need to adapt or completely redesign the packaging. Both autonomous driving functions and ADAS require additional sensors for environment detection[2,11,12]. These are positioned over the entire height of the vehicle. Thus, the number of consumers in the upper half of the vehicle increases sharply, requiring a 3-dimensional view of the cable routing. Fig. 2 shows the positions of the environment-sensing consumers, In which a) are the cameras, b) the lidars, and c) the radars of the Zoox-Shuttle[12]. Moreover some of the actuators for communication with passengers as well as the infrastructure will be positioned in the upper third of the vehicle.

All of the approaches presented show weaknesses when it comes to practicability for use in vehicles. On the one hand, it must be possible to meet application-specific criteria, and on the other hand, the optimization of the overall vehicle system must be aimed for. Optimization of the wiring harness alone can lead to an increase in material or development costs or a reduction in performance.

a) cameras, b) lidars, c) radars of the Zoox-Shuttle

Fig.2 Positions of environment-sensing consumers

2 Optimization algorithms and constraints of cable

The use of platforms in vehicle development makes sense to increase modularity, which reduces costs and time for development. For the method the assumption is made that the approximate position of consumers and power supply system components in the vehicle is known. Concerning Bellman′s optimality principle, the optimization of the total length of all cables can be simplified to the optimization of the cables of each individual link. Thus, it is a single source shortest path (SSSP) problem. The following algorithms are suitable for solving the problem:

- Dijkstra algorithm
- A* algorithm
- Floyd-Warshall algorithm

The A* algorithm requires a lot of memory capacity. The Floyd-Warshall algorithm has a longer computation time compared to the Dijkstra and the A* algorithm. However, since the cost of the edges changes depending on the cable to be laid and the boundary conditions, the consideration of heuristics can even lead to longer computation times. Furthermore, it takes a lot of effort, if even possible to design reliable heuristic data due to the high number of variants. Therefore, to achieve a good result independent of concrete input data, the use of Dijkstra′s algorithm is most promising for this problem. Starting from an initial node, the cost to reach all accessible ones is calculated. This is done stepwise until the final node is reached. The sum of the lowest edge costs thus results in the lowest cost for the entire path. If the start and end points for a cable are known, the cost-optimal path can be found[13].

Therefore, the cost-optimal path does not necessarily correspond to the shortest path. There are other aspects to consider such as reliability (temperature restrictions), safety (cable type dependent restrictions e. g., no HV cables in door areas), packaging (cable distribution), and ease of assembly (bending radius). The cost of the edges is defined and changed depending on the vehicle type and requirements. The cable routing is performed taking these aspects into account. Fig. 3 shows the abstraction of the vehicle geometry by a 3-dimensional grid of edges and nodes. In Fig. 3a) the grid with its initial edge costs can be seen, and in Fig. 3b) they are increased. Since the viewing direction is on the XZ-plane, the Y-plane is not visible.

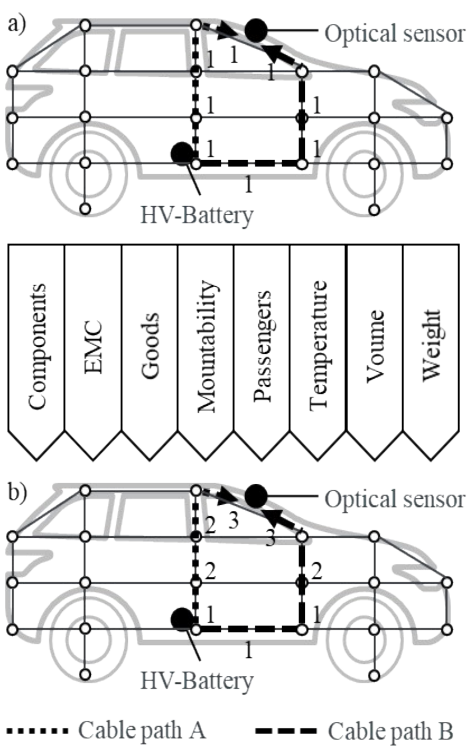


Fig.3 Modification of the edge cost and influencing factors

The nodes are denoted as N_{xyz}, the edges as k_{xyz}, and the edge cost as $g_{xyz}(i)$. The edge cost is displayed by the numbers located below or on the right side of the edge. The current edge cost $g_{xyz}(i)$ results from the sum of all separate costs, for example, cable type CT_{xyz}, the number of cables on an edge CN_{xyz} and the initial cost of the edge $g_{xyz}(0)$ as indicated by Eq. (3).

$$g_{xyz}(i)=\sum_{i=1}^{n} f(CT_{xyz}, CN_{xyz}, g_{xyz}(0)) \quad (3)$$

Other components, EMC and mountability are some of the aspects that can influence the optimal cable path. The transformation of requirements in edge costs helps to identify the optimal path. This does not necessarily have to be the shortest one, but the algorithm takes the path length into account. Different influencing factors cause different costs and cost increases on the edges. This is illustrated by the two possible routings of the cable between the HV-battery and the optical sensor. The initial cost g_{xyz} of the edges is calculated dependent on the minimum distance to the preferred cable paths. Fig. 4 shows an example dataset for a distance dependent cost of a vehicle wiring harness E-structure. The E-structure is adapted for 3-dimensional consideration of the cable paths by adding paths in the Z-direction in the corners of the vehicle. Fig. 4a) displays the cost for the x-direction, b) for the y-direction, and c) for the z-direction. The plot shows one less data point in the respective dimension. The cost of an edge is calculated between two nodes. If the number of nodes is n, the number of edges in the dimension under consideration is n-1, while the number of edges in the dimensions not under consideration is n.

The example dataset uses an exponential cost function. The calculation of the number of nodes $N_{i,\max}$ and edges is based on the vehicle width, length and height as well as the desired granularity of the representation. It is defined by the node distances d_x, d_y, and d_z. according to Eq. (4).

$$N_{i,\max}=\frac{\text{vehicle dimension}_i}{d_i}, \ i=x,y,z \quad (4)$$

In principle, the node distances are freely selectable. The algorithm lays the cables at a 90° angle. This is not possible in reality, since the bending radius r must be selected according to the cable type and diameter. To obtain a measure of the model inaccuracy, a worst-case consideration is performed using the largest bending radius. This radius divides the section on which the bending takes place into two areas. In Fig. 5 these areas are described as a and b and are put into proportion. The lengths l_1 and l_2 of the grid sections result from the

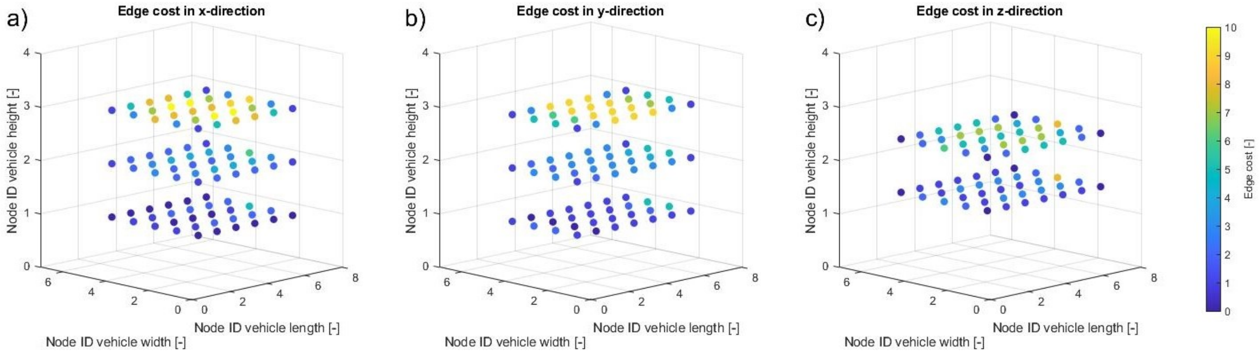


Fig. 4 Edge cost of a vehicle wiring harness E-structure in a) *x*-direction, b) *y*-direction and c) *z*-direction dependent on the distance to preferred cable paths)

node distances. These do not need to be equal due to the different dimensions and number of nodes in the various directions of space. The center point for the radius of the circle section is determined by the nearest corner point to the bending point. The shorter length of the rectangle is subtracted from its coordinate in both axes. It is recommended to aim for a ratio of radius r to l_1 and l_2 as defined in Eq. (5).

$$r \leqslant 0.25 \min(l_1, l_2). \tag{5}$$

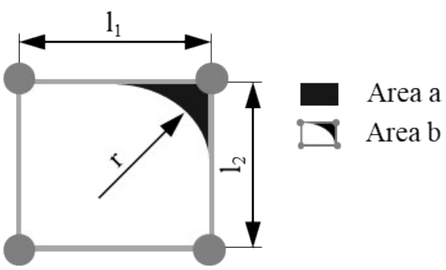


Fig.5 Inaccuracies on bending radius *r* dependent on the area of a grid element ($l_1 \cdot l_2$)

This leads to *a* ratio of area *a* to *b* of 0.013. The error is thus sufficiently small compared to the manufacturing tolerances so that it can be neglected[14]. The ratio of the bending radius to the dimensions of the grid section always depends on the vehicle-type, cable diameter, and the desired level of detail.

3 Framework of optimization

To make the use of the algorithm more user-friendly, it is integrated in a graphical user interface. It supports the handling and the visualisation of the data. Fig. 6 shows the workflow for the optimization of the cable routing by the software tool. First, the vehicle structure is approximated by a 3-dimensional edge-node grid with packaging constraints. Then, one or more components and their interfaces are defined.

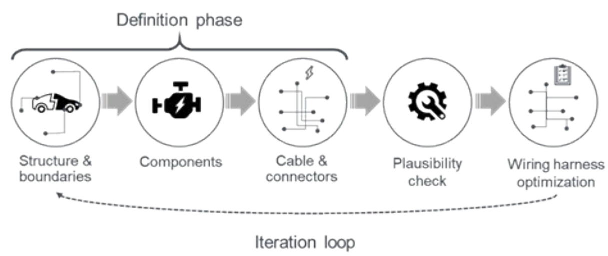


Fig.6 Workflow of software tool for cable optimization

Afterward, the start and end points including the interface are determined. Based on this information, the Dijkstra algorithm finds the optimal path with the lowest edge cost. Then a new component is specified or an existing one is referenced, the start and end points are defined again and the software optimizes the path. This is continued until all cable paths are defined. Finally, the total length and cost are determined and compared to the original cable set to ensure that an improvement has been made. The cable paths are manually inspected and if a different routing is required for packaging reasons, the edge cost matrix, which takes the packaging into account, can be changed. Fig. 7 shows a visualisation of the tools output. The vehicle that is approximated by the knot edge structure is the autoSHUTTLE of the project UNICARagil. The nodes of the vehicle structure are visible. The edges where one or more cable is placed are displayed in the corresponding color. It shows an optimized cable routing for various consumer that are mounted in the real vehicle. The data set includes geometrical positions and the electric specifications.

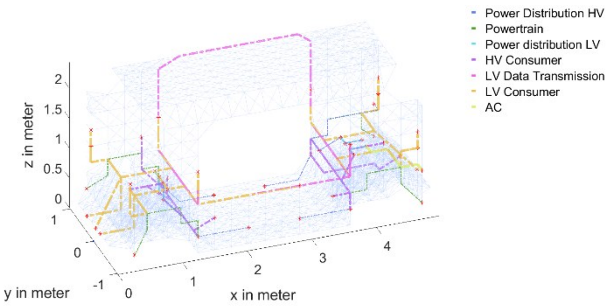


Fig.7　Cable routing with the optimization tool in an automated electric vehicle (autoSHUTTLE)

4　Conclusions

This paper shows a method to optimize cable routing for autonomous EVs. The method supports especially cable routing with multiple voltage levels as it is present in EVs as well as vehicles which have the consumers arranged in higher sections. It consists of an algorithm for routing and a framework to integrate it into the development process of vehicles. Compared to already existing CAD tools, this approach optimizes the wiring harness not only by the distance of the paths. By modifying the cost of the edges, all kind of related aspects can be considered. In the present status the method considers the number of cables on the edge and the distance to preferred paths. In future the research will focus on further aspects e. g. EMV, thermal aspects, vehicle weight balance and software-requirements to improve hardware-software co-design. Furthermore it is necessary to do a parameter study to find meaningful parameter sets, cost functions and correlation between parameters.

This tool aims to support in the early development phase when only the entire vehicle specifications are defined e. g. target driving power, the voltage of the HV-power supply system, and vehicle dimensions. It will support the evaluation of power supply system concepts by providing detailed information on the wiring harness. Already defined constraints can be taken into account and an estimation of the cable length and weight is determined. Furthermore it supports the evaluation of packaging concepts as it is possible to consider all electric sources and sinks as well as further packaging limitations.

References:

[1] ZF Group. Autonomous Transport Systems[R]. Friedrichshafen: ZF Group, 2022.

[2] Zoox Inc. Introducing Zoox: Built for riders, not drivers[EB/OL]. Foster City, California: Zoox Inc, 2022. https://zoox.com/vehicle/.

[3] Lohr Group. le cristal. Mobilitätslösung. 100% elektrisch, flexibel und vernetzt[EB/OL]. [2023-03-06]. https://lohr.fr/lohruploads/2020/09/2020-09-plaquette-cristal-de.pdf.

[4] KONSORTIUM U. Projekt-Website: UNICARagil [EB/OL]. [2022-11-16]. https:// www.unicaragil.de/impressum.

[5] MAYER G. Positionspapier: Schlüsselrolle der EE-architektur und der bordnetze für das automobil der zukunft [EB/OL]. Berlin: eNOVA—Strategiekreis Automobile Zukunft, 2020. [2023-03-06]. https://www.strategiekreis-automobile-zukunft.de/files/enova-position-bordnetze-und-fahrzeugarchitektur.pdf.

[6] NAFISEH M. Geometric-based optimization algorithms for cable routing and branching in cluttered environments [D]. Clemson: Clemson University, 2020.

[7] NAFISEH M, GEORGES F. An optimization framework for the design of cable harness layouts in planar interconnected systems [J]. Journal of Mechanical Design, 2021, 144 (1): 011701. DOI: 10.1115/1.4051685.

[8] NECKENICH J. 3D-Master-Leitungssatz—Konzept zur entwicklung von leitungssätzen als 3D-Master in einem realistischen, vollständigen DMU-Modell [D]. Saarbrücken: Naturwissenschaftlich-Technischen Fakultät der Universität des Saarlandes, 2017. DOI: 10.22028/D291-26986.

[9] MOORE S. Modeling and optimizing wire harness costs for variation complexity [EB/OL]. Mentor Graphics Corporation, 2016. DOI: 10.4271/2016-01-0107.

[10] BRAUN L. Modellbasierte design-space-exploration nicht-funktionaler auslegungskriterien des fahrzeugenergiebordnetzes [D]. Karlsruhe: Karlsruhe Institut of Technology (KIT), 2018. DOI: 10.5445/IR/1000081298.

[11] BAXTER J A, MERCED D A, COSTINETT D J, *et al.* Review of electrical architectures and power requirements for automated vehicles [C]//2018 IEEE Transportation Electrification Conference and Expo (ITEC). LongBeach, CA: IEEE, 2018: 944. DOI: 10.1109/ITEC.2018.8449961.

[12] Zoox Inc. Autonomy. The 'full-stack' behind autonomous driving [EB/OL]. [2022-07-05]. https://zoox.com/autonomy/.

[13] DIJKSTRA E W. A note on two problems in connexion with graphs [J]. Numer Math 1, 1959: 269. DOI: 10.1145/3544585.3544600.

[14] Hopa Kabelkonfektion GmbH & Co. KG. Längentoleranz[EB/OL]. [2022-07-05]. https://www.hopa—gmbh.de/zertifizierung.