Data Resolution and Future Challenges in Automated Undersea Cable System Design

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***Abstract*—Undersea optical cables form the backbone of global Internet infrastructure, carrying nearly 99% of international Internet data. As demand for high-speed and reliable connectivity continues to grow, optimizing undersea cable path planning has become essential for reducing costs, mitigating risks, and ensuring high-quality service delivery. While traditional manual planning methods remain widely used by cable system designers, surveyors, and planners, the increasing complexity of cable deployment necessitates the integration of automated methods that leverage advanced computational techniques to enhance efficiency and decision-making. This paper reviews the state-of-the-art in cable path planning and system design, emphasizing the important role of data density in achieving optimal cable paths. In particular, we present realistic path-planning scenarios on the Earth's surface and describe the Fast Marching Method (FMM), a computational approach that efficiently determines optimal routing based on available data. Simulation results show that increasing map resolution, along with accompanying data at the higher resolution, significantly enhances path planning accuracy, reduces deployment costs, and improves risk assessment, underscoring the importance of acquiring and utilizing high-density data. This understanding leads to a discussion of the challenges of data acquisition and computational scalability in processing large-scale datasets, and the importance of collaboration between cable system engineers, geospatial data scientists, and software developers. This paper proposes a collaborative framework in which automated algorithms complement traditional planning methods, enabling cost-effective solutions that continually adapt and become more effective through expert feedback. This research contributes to a more resilient, efficient, and adaptive global undersea communication network, paving the way for the next generation of intelligent, optimized cable infrastructure.**

***Index Terms*—Undersea cable path planning, triangulated manifold, resolution, high-density geophysical data, challenges, fast marching method**

I. INTRODUCTION

Undersea cables are crucial in the transmission of information, as they carry over 99% of the global Internet traffic. TeleGeography (https://www.submarinecablemap.com/) revealed that 378 undersea cables, running over 1.2 million kilometers, are in service as of early 2019. The basic construction cost of undersea cables is approximately \$20,000-\$28,000 per kilometer [1, 2].

Undersea cables have a lifespan of about 25 years, currently, there is a boom in undersea cable replacement [2, 3]. With the growth of Internet traffic and the consequential demand for undersea cables, undersea cable construction and path planning methods are becoming increasingly important in the provision of reliable and efficient Internet services. There is an urgent need for cost-effective and reliable undersea cable system design solutions.

At the heart of future directions in automated cable path and system planning is the need for extensive high-density data. This article illustrates numerically the importance of high-density data using realistic examples. We demonstrate the importance of developing scalable algorithms applied to high-density data and complementing missing data in areas where available data is insufficient.

This paper provides two realistic examples: a long-haul cable path planning problem in the North Atlantic Ocean region and cable system optimization in the Mediterranean region. In the two examples, we aim to minimize the total weighted cost of the undersea cable systems, where the weighted cost of the cable is related to the cable laying cost, attributed to labor, licenses, protection levels, etc, and cable break risks arising from seismic hazards, soil type, seabed slope, fishing activities, etc, as discussed in [2, 4].

From the numerical results of the North Atlantic Ocean region, we demonstrate that if a factor of 12.34 increases the map resolution, the weighted cost of a cable system is reduced by 2.26%. In the Mediterranean region, reducing the distance between grid data points by a factor of 6.67 can result in a cost savings of 6.1%. The comparisons of these results obtained at different data resolution levels can provide a reference for cable path planning engineers when considering the importance of the data resolution level.

Our contribution in this paper is to quantize the importance of data density for high-quality results. We present the *Path Trajectory Segmentation Calculation* (PTSC) method, which calculates the cost differences between manifolds at varying resolutions for optimized cable path planning. To assess the improvement achieved by increased resolution, we

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This work was supported by the Hong Kong Innovation and Technology Commission (InnoHK Project CIMDA), by a grant from the Research Grants Council of the Hong Kong Special Administrative Region, China (CityU 11201922), and by the Shenzhen Municipal Science and Technology Innovation Committee under Project JCYJ20180306171144091. *(Corresponding author: Zengfu Wang.)*

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have applied the PTSC approach in two real-world examples, including a 6,500 km transoceanic cable and cable network optimization problem. We also discuss the challenges of acquiring high-density data and scalability issues in large-scale planning, and so providing insights for future research. Lastly, we propose a collaborative framework between designers and automated developers, where automated algorithms complement traditional methods and drive cost savings, continuously learning from expert feedback to refine designs.

II. Current Industry Practice and Related Work

Current industry practice is to perform cable routing manually for much of the design process, and the MakaiPlan software tool (https://www.makai.com) is widely used to assist in this process. MakaiPlan does not provide automated optimization for path planning; it can only automatically find the shortest distance along a great circle as a series of Rhumb lines. This path is then modified manually to reduce costs associated with risk and other factors.

The length of long-haul cables can span thousands of kilometers, so manual path planning without using a scalable and automated software tool is costly and may not achieve the desired optimal cost-risk trade-off. Undersea cable path planning is time-consuming and labor-intensive, especially when planners need to handle adjustments to their work schedules manually. Automated planning methods can speed up the planning process and find the best cable paths by fully analyzing and utilizing the precise data of the geography of the seafloor and potential crises of human activities.

Wang *et al.* [5] provides a methodology for path planning optimization for undersea cables connecting two end nodes, or a given site to an existing cable network on the Earth's surface. A key innovation is the use of the Fast Marching Method (FMM) as a continuous extension of Dijkstra's algorithm, allowing paths to traverse through the interiors of triangles rather than being constrained by discrete grid points while taking into account multiple design considerations. The FMM avoids the weaknesses of Dijkstra's algorithm [6] by solving the Eikonal equation as the grid size of the triangulated manifold approaches zero.

Wang *et al.* [4] introduced a novel automated approach for submarine cable path planning, leveraging Simulated Annealing to optimize the weighting of various design considerations [2]. An important aspect of this work is its validation through a real-world comparison, demonstrating that the algorithm-generated path closely aligns with an actual long-haul cable route between the same end nodes. This provides strong evidence for the practical applicability and reliability of the method in real-world submarine cable deployment.

Zhao et al. [7] proposed a heuristic approach for submarine cable route optimization, integrating Ant Colony Optimization (ACO) with a geographical cost-risk model. This multi-objective framework dynamically explores cost-effective and reliable paths, effectively avoiding high-cost and high-risk regions. More recently, considering model-free weights on different design considerations, Zhao et al. [8] proposed a Local Pareto to Global Pareto optimization method and an offline collaborative reinforcement learning framework to decouple and optimize submarine cable cost and risk. Experimental results demonstrate that this approach outperforms ACO and Multi-Agent Cross Reinforcement Learning in cost and risk reduction.

Blaise et al. [9] introduced a flexible approach that incorporates curvature constraints into submarine cable path planning. Their work explicitly accounts for the bending stiffness of undersea cables or pipelines and the maneuverability limitations of cable-laying devices. On the other hand, Dijkstra's algorithm with its limitations, compared to FMM [6], is used for cable path planning.

Wang et al. [3, 10, 11] introduced an advanced framework that integrates FMM with dynamic programming algorithms, known as the DAG-Least-Cost-System algorithm. Wang et al. [3] optimized the placement of Branching Units (BUs) and cable landing stations (CLSs) to minimize overall network costs. Lagrangian relaxation techniques were applied [10] to enforce latency constraints between specific node pairs, ensuring efficient data transmission. A weighted Steiner tree model was proposed [11] to optimize bandwidth allocation between node pairs, improving network capacity planning.

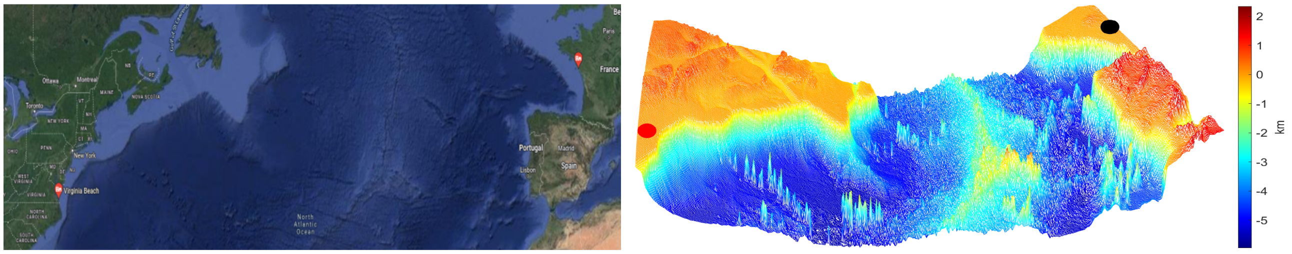
Automated methods offer invaluable support in designing cable systems, enabling more efficient and effective route optimization, as well as an ability to quickly and quantitatively assess the effects of different risks and costs to the cable route. The approach provided in this paper is essential for undersea cable path planning on a realistic model of the Earth's surface. This approach takes into account the seabed's topography, designated risk areas, and zones where cable laying is prohibited, making it more complex than traditional path planning in Euclidean space, where connections between nodes are typically represented as straight lines.

III. Problem Model

We approximate the earth's landforms in the objective region by a triangulated piecewise-linear 2-dimensional (2D) manifold in 3D Euclidean space, as shown in Fig. 1(b) and Fig. 3(b). Each mesh node x in the triangulated manifold is represented by its 3D coordinate, specifically, *latitude*, *longitude*, and *altitude*, together with a given *weighted cost*.

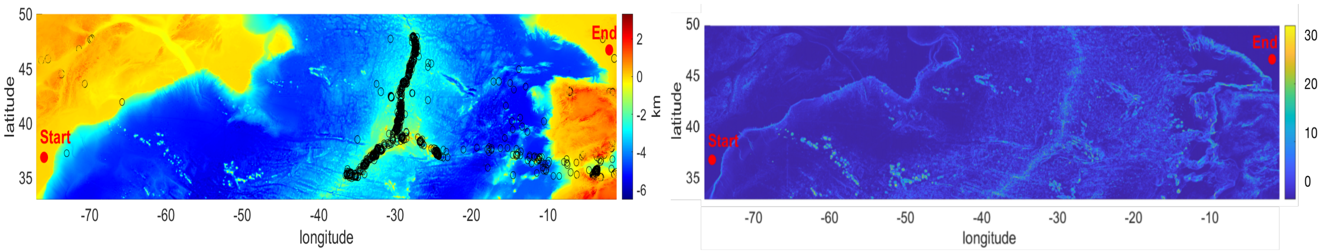
We employ the repair rate model to quantify the cost and risks of cables rather than probability models that are constrained to particular scenarios with simplifying assumptions. This methodology facilitates the conversion of a multi-objective optimization problem into a single objective through the application of weighted cost functions. The basic construction cost, which involves the labor and materials, is \$20,000-\$28,000 per km, which is estimated based on the International Cable Protection Committee (ICPC)(https://www.iscpc.org/publications/recommendations/) report and relevant research [2, 3]. The cable breakage risks that contribute to the weighted cost are discussed below.

The weighted cost of seismic hazards, denoted by d, is typically measured in terms of the predicted peak ground velocity (PGV). The weighting of the PGV can be adjusted according to the intensity of different ground motions. The



(a) Terrain map of Region $\mathbb{B}$. Source: Google Earth.

(b) Triangulated manifold of Region $\mathbb{B}$.



(c) Historical earthquake locations in Region $\mathbb{B}$.

(d) Slope map of Region $\mathbb{B}$ (°).

Fig. 1: The Overview of Region $\mathbb{B}$. Source: Google Earth.

risk from soil type and fishing activities could, for instance, be assessed through data collection in the target area, combined with the understanding and knowledge of experienced undersea cable planners. For a detailed description of our modeling and methodology, the reader is referred to [2, 3, 5, 12].

Sea depth is an important component of the weighted cost. ICPC recommends that the part of the cable in shallow water should be as short as possible. The cable should preferably be laid in deep water, thereby reducing human activity risks.

We enforce these depth constraints by imposing a piecewise cost function involving the division of the objective area into three sections according to depth. In this particular algorithm, we assign a fixed cost value, a_1, to the depth cost when the cable is going over land. This represents a substantial penalty designed to prevent cable exposure on land, where the cable would require enhanced protection and hence high cost. For depths $d(x)$ at location x ranging from 0 to -1km, the cost decreases with increasing depth according to $a_1 \cdot e^{-4d(x)}$. For depths greater than -1km, the cost continues to decrease with depth, following the formula $a_1 \cdot e^{-3-d(x)}$. As stated, this is specific to our current algorithm, and adjustment to other depth cost models is relatively straightforward.

The seabed slope is another critical factor in the total cost, including risk penalties. A steep terrain can potentially capsize a remotely operated vehicle during cable burial, as discussed in [2, 4]. According to recommendations of the ICPC, undersea cables should be laid only in locations with no more than a 25° slope to the horizontal. In industry practice, a slope of less than 10° is considered acceptable for cable laying; however, slopes exceeding 10° present challenges. In our model, $p(x)$ represents the slope at mesh nodes x; for slopes between 10° and 20°, we assume a linear relationship between cost and slope. The formula for the cost in such cases is $a_2 \cdot \frac{p(x)-10}{10}$. For slopes exceeding 20°, the costs escalate significantly, calculated using $a_2 \cdot e^{p(x)-20}$.

We set the cost for slopes greater than 25° to infinity, effectively avoiding all areas with seabed slopes steeper than 25°. This approach ensures that the cable route is as smooth as possible, minimizing the risk of cable damage due to abrupt changes in angle. It is important to note that the seabed slope data is sensitive to the resolution of the measurements. Lower-density data may lack detailed slope information, whereas this can be captured more accurately on higher-resolution maps.

The weights assigned to different design considerations may vary because they have varying degrees of impact on the risk of undersea cable breaks. The selection of weights can be determined by referencing the Analytic Hierarchy Process (AHP) used in [2], which involves using a comparison matrix to rank the priorities of the design considerations. Alternatively, weights can be derived from the method mentioned in [4], which uses the FMM/Simulated Annealing (SA) to learn from manually designed real-world undersea cable paths by experts as mentioned in the related work. We use the AHP to determine the weight values for seismic hazards, water depth, and slope in this paper. We will describe the weight value in detail for each example in Section IV.

In this paper, cable path planning is treated as a static process; that is, a given set of data is used to determine the optimal path. During the path planning stage, and before the cable is laid, if new risk data, protected areas, or exclusive economic zones are introduced, the relevant weighted cost function needs to be updated, and this may involve adding components of infinite cost. Then the FMM is executed again to obtain the new optimal path. In an industrial implementation of this algorithm, the user will be able to adjust the weights on the various factors to accommodate their assessments of their importance.

Any pair of grid nodes can be connected by a continuous curve in the manifold, representing a cable path connecting these two nodes in the region. The points in the path are calculated using FMM, which computes the arrival time (cumulative cost) for each grid point by solving the appropriate Eikonal equation. It iteratively selects the point with the shortest arrival time from a priority queue for expansion and, upon reaching the goal, backtracks along the gradient descent of the arrival time field to generate the optimal path from the goal to the start. Accordingly, during path planning, the FMM algorithm minimizes the summary function of the weighted costs. This allows it to efficiently balance different risks and costs. Finding the optimal path ensures both economic efficiency and reliability.

Increasing map resolution improves the accuracy and quality of the cable path and overall system because of the additional information in the refined map, but it may lead to an increase in costs, as the additional information introduces more constraints and also provides a more accurate means for cost evaluation. In the following, we discuss the simple case of a point-to-point path, but the discussion easily extends to a general cable system.

For instance, by using the same optimal path (Path-I) resulting from a lower resolution manifold in the higher resolution case, we observe a significant increase in costs over the optimal higher resolution path (Path-II), which may be shorter than Path-I. Comparing the cost of Path-I and Path-II under the higher resolution enables us to quantitatively assess the value of increased resolution. The cost of Path-II can be obtained by applying the FMM approach.

To calculate the cost of Path-I, the PTSC method is used [13]. PTSC applies FMM on the lower-resolution manifold to obtain Path-I and its cost (Cost-I). The end nodes of each segment in Path-I are transferred to a higher-density model. FMM is then run on each segment to calculate the new cost of Path-I (Cost-II). Finally, FMM is applied to the same endpoints in the higher-density model to obtain a new cable path and its cost (Cost-III). The comparison of Cost-II and Cost-III reflects the benefit of higher resolution.

IV. NUMERICAL RESULTS AND DISCUSSION

To assess the improvement achieved by increasing resolution, we apply here our approach described in Section III in two real-world undersea cable path planning scenarios, including a point-to-point long-haul undersea cable and a cable network. Data for the earth's surface were obtained from the General Bathymetric Chart of the Oceans (GEBCO, http://www.gebco.net/) with 30-arcsecond increments in longitude and latitude. This is the most detailed data that is publicly available.

A. Point-to-point long-haul undersea cable

In this example, we demonstrate the application of FMM for point-to-point long-haul undersea cable path planning with the start point located at Saint-Hilaire-de-Riez, France (46.711°N, 1.984°W) and endpoint located at Virginia Beach, VA, United States (36.852°N, 75.979°W) in a target region $\mathbb{B}$ which spans from its northwest corner (50.000°N, 1.000°W) to its southeast corner (33.000°N, 77.000°W) (see Fig. 1 (a)).

In this case, in addition to the basic construction cost per kilometer related to the length of the undersea cable, we also take into account the potential impact of earthquake disasters as an additional cost, as well as water depth, and seabed slope, as discussed in Section III. We set the average basic cost of the cable in this area at $28,000 per km, based on industry records (https://subtelforum.com/); this reflects the average construction cost of cables installed in similar sea regions over recent years. The weights for the basic construction cost and the three risks are set at 0.1927, 0.2288, 0.0593, and 0.5192, respectively; these are calculated using the AHP method discussed in Section III.

Additionally, we establish the values of d, a_1, and a_2 at $3 million each, representing the penalty cost associated with potential cable repairs. For a comprehensive discussion of all the components of the weighted cost function, readers are encouraged to read [2, 4]. Earthquake data in the past 50 years for Region $\mathbb{B}$ was sourced from the USGS (https://earthquake.usgs.gov/). Fig. 1(b) shows earthquake locations on an elevation map, while Fig. 1(c) displays the seabed slope. We aim to find a cost-effective cable path between start and end points with minimal total weighted cost.

Firstly, we apply FMM in $\mathbb{B}$ with lower-density data to find the optimal cable path, $\mathbb{B}_{\mathrm{I}}$, composed of contiguous segments constrained to single grid triangles in the lower-resolution manifold. The length and the cost of $\mathbb{B}_{\mathrm{I}}$ are denoted by $\mathrm{Length}\left(\mathbb{B}_{\mathrm{I}}\right)$ and $\mathrm{Cost}\left(\mathbb{B}_{\mathrm{I}}\right)$, respectively. Next, we apply PTSC to calculate the length and cost of $\mathbb{B}_{\mathrm{I}}$ in the higher resolution manifold which is denoted as $\mathrm{Length}\left(\mathbb{B}_{\mathrm{II}}\right)$ and $\mathrm{Cost}\left(\mathbb{B}_{\mathrm{II}}\right)$, respectively. Finally, in a higher resolution manifold, we directly apply FMM to obtain the minimum weighted cost path, $\mathbb{B}_{\mathrm{II}}$ with length and the cost $\mathrm{Length}\left(\mathbb{B}_{\mathrm{III}}\right)$ and $\mathrm{Cost}\left(\mathbb{B}_{\mathrm{III}}\right)$.

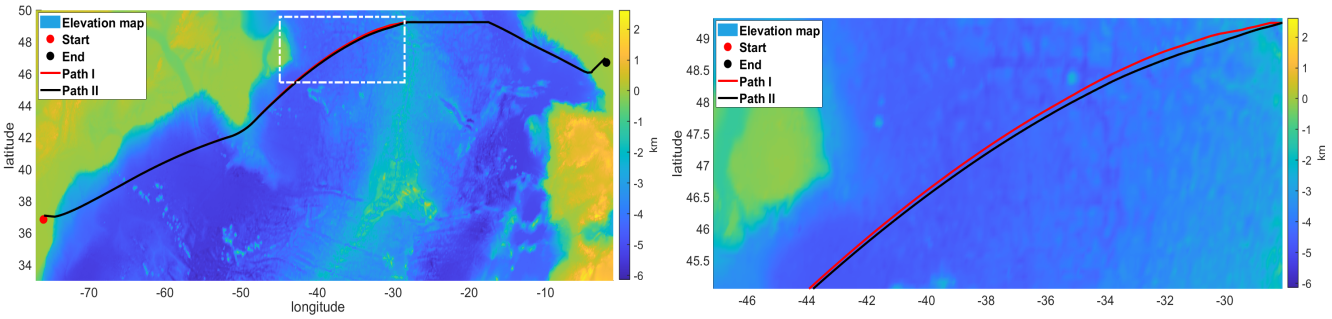
$\mathbb{B}_{\mathrm{I}}$ and $\mathbb{B}_{\mathrm{II}}$ are depicted in Fig. 2 with metrics in Table I. The comparison of Cost ($\mathbb{B}_{\mathrm{II}}$) with Cost ($\mathbb{B}_{\mathrm{III}}$) and Length ($\mathbb{B}_{\mathrm{II}}$) with Length ($\mathbb{B}_{\mathrm{III}}$) shows that increasing the map resolution by a factor of 12.34 leads to significant improvements in path optimization outcomes. Specifically, the optimal path length for $\mathbb{B}_{\mathrm{II}}$ is 142.61 km shorter than that of $\mathbb{B}_{\mathrm{I}}$. Additionally, the associated cost, which includes risk considerations, is reduced by $1.92 million, approximately 2.26%.

B. Undersea cable system

In this example, we apply the DAG-Least-Cost-System algorithm, proposed in our previous paper [3, 10] for cable system optimization in Region $\mathbb{D}$, which spans from its northwest corner (45.000°N, 0.000°E) to its southeast corner (36.000°N, 11.000°E). We aim to design a minimum cost cable system with a Steiner tree topology to connect five terminal nodes, Marseille (A), Sardegna (B), Algiers (C), Barcelona (D), and Annaba (E), as shown in Fig. 3(a).

Based on the investigation of the total length and cost of undersea cable systems (i.e., Medloop) in the Mediterranean area, we set the average basic cost of the cable at $25,000 per km and BU cost at $1 million. Slope and elevation data for $\mathbb{D}$ are also shown in Fig. 3(b). Parameters a_1 and a_2 are set to $3 million each, consistent with the first example.

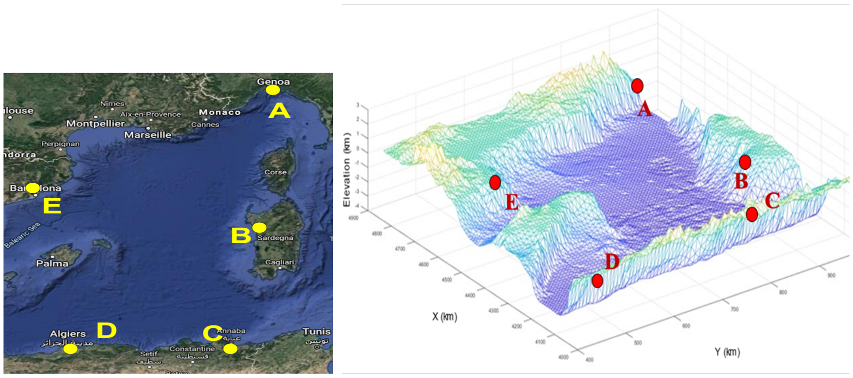
We formulate the cable system optimization as a Steiner minimal tree (SMT) problem, where each Steiner node models a BU. For a given topology, we apply the DAG-Least-Cost-System [3, 11] algorithm on the manifold of the



(a) Overview of the results (Path I and II).

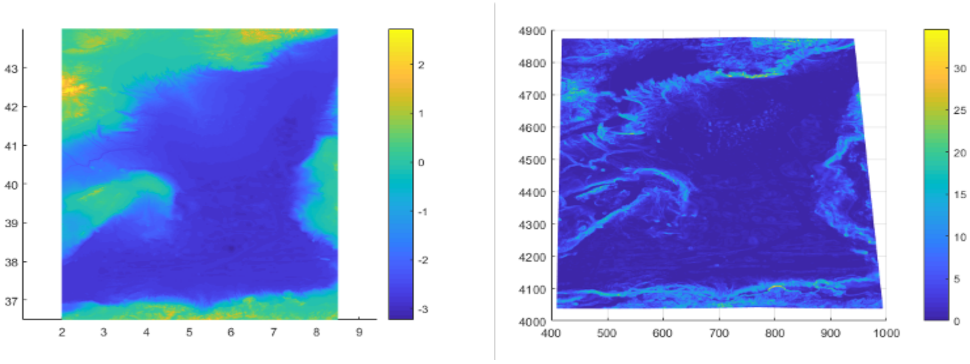
(b) A partially enlarged view of the white box area in Fig. 2(a).

Fig. 2: Long haul undersea cable path planning results in Region $\mathbb{B}$.



(a) Terrain map of Region $\mathbb{B}$. Source: Google Earth.

(b) Triangulated manifold of Region $\mathbb{D}$.



(c) Depth map of Region $\mathbb{D}$ (km).

(d) Slope map of Region $\mathbb{D}$ (°).

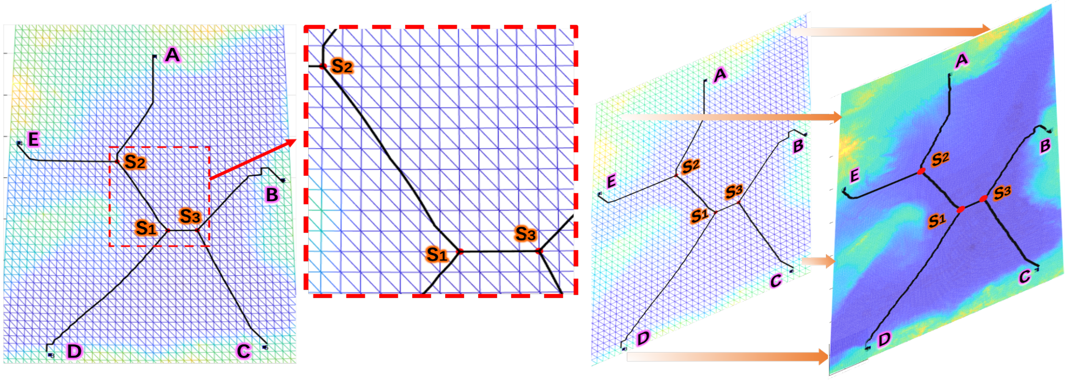
Fig. 3: The Overview of Region $\mathbb{D}$. Source: Google Earth.

region $\mathbb{D}$ with lower-density data where the average distance between two adjacent points is 16.661 km. The result of the cable system at low resolution, $\mathbb{D}_{\text{I}}$, includes three BUs at (41.1625°N, 4.4958°E), (39.6625°N, 5.6625°E) and (39.6625°N, 6.3292°E). Total cost with risk penalties, total cost without risk penalties, and total length are displayed in Fig. 4(a) and Table I.

We then transfer the paths and BU locations from $\mathbb{D}_{\text{I}}$ to a higher-density data manifold which has 6.67 times the data resolution of the lower-density manifold, with an average distance of 2.451 km between adjacent points. Using the PTSC method, we compute Cost ($\mathbb{D}_{\text{II}}$) and Length($\mathbb{D}_{\text{II}}$) for the same network $\mathbb{D}_{\text{I}}$, now with higher-density data. While the cable path trajectories are the same in lower-resolution and higher-resolution maps, Cost ($\mathbb{D}_{\text{II}}$) and Length($\mathbb{D}_{\text{II}}$) are more reliable because the seafloor information has more details in the higher-resolution maps.

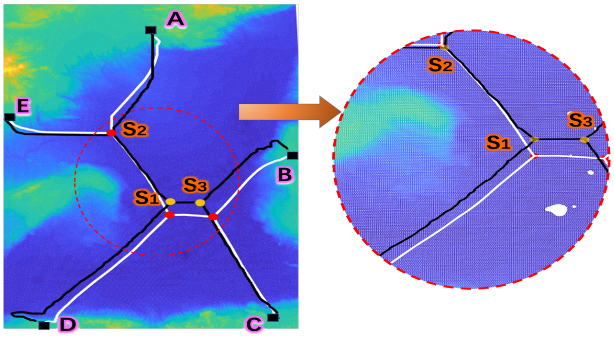
These are compared to the true optimal path, $\mathbb{D}_{\text{II}}$, obtained via the DAG-Least-Cost-System algorithm with Cost ($\mathbb{D}_{\text{III}}$) and Length($\mathbb{D}_{\text{III}}$) shown in Fig. 4(c) and Table I. The BUs in are relocated to (41.1958°N, 4.4492°E), (39.4625°N, 5.6292°E) and (39.4292°N, 6.3625°E).

As shown in Fig. 4(c), the higher-resolution path is smoother, shorter, and less costly. With high-density data, $\mathbb{D}_{\text{II}}$ is 53.61 km shorter than $\mathbb{D}_{\text{I}}$, and the associated costs are significantly lower: the cost with risk is reduced by \$2.8



(a) Optimal result in the lower resolution manifold.

(b) Lower resolution paths map to higher resolution manifold.



(c) Overview of the results (System I and II).

Fig. 4: Undersea cable system optimization.

(6.1%) million, and the cost without risk is reduced by $1.55 (8.3%) million.

Comparison of results obtained at different data resolution levels can serve as a valuable reference for cable path planning engineers when assessing the importance of data resolution. However, as we aim to provide an initial path that can be manually adjusted, excessively fine resolution may not necessarily result in significant cost savings in the final path. Our objective is to select an appropriate resolution that adequately captures the topography and risk factors of the seabed.

V. FUTURE CHALLENGES AND OPPORTUNITIES

Given the complex considerations and high costs of laying and maintaining undersea cables, the *Right First Time* principle in the cable path planning process is important. Once the equipment is deployed, it is too expensive to change the cable path (https://telecoms.com/opinion/overcoming-the-challenges-of-subsea-cable-route-planning/). Automated planning tools, as described here, can support the *Right First Time* principle and speed up the cable planning process based on precise data for the subsea environmental information related to the costs and risks. Automated planning tools have proven their data analysis and computing power to go beyond human capabilities in this area. These tools can provide invaluable assistance in assessing the optimal solutions for cable system design.

A. *Two Future Challenges*

We face two challenges in achieving high-quality automatic undersea cable system design (or path planning) and enhancing the commonly used manual approach of cable designers and surveyors.

The first is the acquisition, typically by exploration and remote sensing, of high-density seafloor topographic data and ground motion information for the area under consideration. Bathymetry data is essential in cable path planning, navigation safety, and many other applications. Detailed seafloor topographic information and other basic factors, including natural hazard risk, location of protection area, existing pipelines and cables, human activity, and geopolitical instability, are important for optimizing the cable system [4, 7]. However, most oceans are still unexplored and unmapped. Direct measurements have systematically mapped only a tiny fraction of the seafloor. The remaining bathymetry data is estimated by satellite altimetry and sonar soundings, which can only provide an approximate estimate of the surface of the seafloor. In fact, a wealth of data has been collected by surveying companies for decades. Unfortunately, such data is not publicly available because it is typically owned by the customers of surveying companies and, therefore, cannot be accessed without their permission. There are initiatives for data sharing and one of them is the GEBCO.

GEBCO provides a range of bathymetric data sets and data products. It seeks to provide the most authoritative

TABLE I: FMM-based path planning performance with changing resolution.

Region	Path /System	Resolution (km)	Total length (km)	Total cost including risk penalties (million$)	Total cost excluding risk penalties (million$)	Figure
North Atlantic Ocean $\mathbb{B}$	$\mathbb{B}_{\text{I}}$	10.489	6416.67	84.29	34.62	Fig. 2(a)
	$\mathbb{B}_{\text{I}}$	0.850	6442.95	84.97	34.76	Fig. 2(a)
	$\mathbb{B}_{\text{II}}$	0.850	6301.34	83.05	33.99	Fig. 2(a)
Mediterranean $\mathbb{D}$	$\mathbb{D}_{\text{I}}$	16.661	1672.01	29.36	17.39	Fig. 4(a)
	$\mathbb{D}_{\text{I}}$	2.451	1684.31	45.62	18.51	Fig. 4(b)
	$\mathbb{D}_{\text{II}}$	2.451	1630.70	42.82	16.96	Fig. 4(c)

publicly available bathymetry in the world's oceans. GEBCO is working to make connections between its customers and some surveying companies so as to release and communicate the data. The first collaboration was established in early 2018 with Fugro, a large offshore company providing surveying services, with the opportunity to collect more bathymetric data during transits as a form of crowdsourced contribution as they move vessels from project to project.

In addition to inadequate bathymetric data, dense detailed data of seismic ground motion is also unavailable in many areas of the world with a history of earthquakes. USGS provides comprehensive data sets in some areas, including PGV, earthquake magnitudes, focus depth, fault types, and locations, locations of epicenters of past earthquakes, and soil types. However, most seabed areas have not been surveyed. Researchers have developed methods to create estimated hazard maps on the historical records of earthquakes for areas where the PGV data is unavailable.

The second challenge in cable system optimization is dealing with the computationally prohibitive massive data size arising from the use of very high-fidelity dense topographic maps. The scalability of the algorithms that use high-density data needs to be improved.

Wang *et al.* [4] mitigated the computation difficulties associated with large search spaces by using the FMM to find the shortest path over a manifold. Compared to discrete graph-based raster algorithms, FMM can significantly reduce the runtime for finding optimal paths. However, for long-haul cables over 6,500 km, even with FMM, the cable routing process is complex in a high-density data model with billions of nodes [4]. Because FMM is inherently sequential and thus very time-consuming, attempts to parallelize it so far have been limited in performance. Additionally, as FMM provides optimal solution given the data [6], in this paper, we do not consider heuristic (non-optimal) algorithms, such as the A^* search, ant colony optimization, and reinforcement learning-based methods. We also do not consider Dijkstra's algorithm because it finds more restricted solutions to that of FMM, as its paths are constrained to the grid edges of the model. A detailed comparison between Dijkstra's algorithm and FMM can be found in our previous work [13].

Another approach to addressing big data challenges for algorithms is the multi-resolution approach, which iteratively adjusts the path by diluting the resolution of the data in regions far from the current path and increasing the resolution closer to the current path. Wang et al. [14] introduced an Adaptive Parallel FMM, which incorporates dynamic multi-resolution analysis. In an ultra-long-distance undersea cable path planning example, the running time was reduced by more than 81% compared to the traditional parallel FMM. Such an algorithm may give good-quality path-planning solutions. In [15], deep learning (DL)-based approximation techniques are used to provide approximate solutions to the Eikonal equation. This might provide a mechanism to replace FMM for cable path planning in computationally intensive scenarios, though FMM is known to be highly efficient while providing provably optimal results within the resolution of the data. A study to compare the accuracy of DL against FMM for problems that are not too computationally intensive would be interesting.

Furthermore, the challenges of processing massive amounts of data include loading information from billions of nodes into a computer, which requires distributed memory rather than shared memory technology. To load the data into one computer, distributed-memory parallel computation can be adopted. A High-Performance Computing system can be used as a distributed computing platform to overcome the scalability problem, using a load-balancing scheduler and multiple threads and nodes that are interconnected with high-performance switches.

B. Combining the Automatic and Manual Processes

High-quality automatic solutions for path planning are important because they can provide high-quality cable path planning and/or cable system planning for surveyors and designers that can be used as a benchmark to compare with their manual cable path planning. This enables design improvements facilitated by the use of these automated solutions. As well as the benchmarking role, this interaction will permit feedback to the designers of the automated cable path/system designers or further improve their solutions. Such collaboration between cable designers and surveyors, on the one hand, and automated solutions designers, on the other, will lead to further improvement in the challenging and essential task of undersea cable path and system planning.

As mentioned in Section II, the path resulting from MakaiPlan is modified manually to reduce costs associated with risk and other factors. Inevitably, this can produce paths that are very different from the optimal one. Compared to MakaiPlan, our automated method can provide a better initial path. Because our method takes into account the various factors we have discussed (labor, licenses, protection levels, cable break risks, etc. [4]) when doing cable routing. By starting with an initial optimized path using our automated approach, and collaborating with experts in manual routing, we are able to achieve much better cable routing.

With over a million kilometers of internet cables expected to be added in this decade, billions of dollars will be invested in these new cables. Automation provides significant cost savings opportunities for efficient cable path planning solutions. Cable path planning optimization methodologies will also contribute to Internet resilience. We believe, taking into account cost savings and Internet resilience improvement, our work on cable path planning optimization solutions can make a significant societal and industrial impact.

VI. CONCLUSION

The importance of undersea cables cannot be overemphasized. They are the connectors for people and society that help drive the world economy. The manual approach for cable path planning currently used by the industry cannot achieve optimal paths and is very labor-intensive. Automated means for undersea cable path planning are needed to reinforce the manual approach commonly used by cable path and system planners, designers, and surveyors.

This article discusses the importance of data density in achieving high-quality undersea cable paths and system planning. To this end, we have proposed the PTSC method to calculate the difference between the costs in the lower and higher resolution manifold. We have considered realistic path planning examples over the surface of the earth and provided numerical results for a point-to-point long-haul (6,500 km) undersea cable and a cable system that involves multiple undersea cables.

We have summarized the future challenges of obtaining the required levels of high-density data to enable high-quality automated path planning over thousands of kilometers, and the scalability challenges of algorithms using such high-density data.

Finally, we have described our vision for collaboration between cable system designers and automated solution software designers. Automated path planning algorithms will be used by the industry as a benchmark to complement their manual approach and achieve significant cost savings for all stakeholders. Automated path planning algorithms will benefit from the inclusion of new considerations learned from experts, and vice versa, experts will improve their design with the help of our results.

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