Cable Routing Optimization of a Cable-Driven Robot

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Introduction and Objectives

The cable actuation makes the robot structure light, robust and operable via a minimal set of onboard electronics. These features allow the robot to operate in hostile environments with high temperatures or chemical hazards since the motors and most of the electronics can be safely positioned at the base of the robot. At the same time, cable routing can be very complex, and this can have a significant impact on system performance. The interaction between the cables and the structure can increase the cabling loads considerably, thus decreasing the payload of the robot.

The robot consists of five joints as shown in Fig. 1. Each joint is driven by two antagonist cables. There are 20 ports on the joint, arranged in a circumference, through which the cables can pass [1]. The cable routing matrix **T** describes the ports through which the cables pass. **T** is an upper triangular matrix, and any element $t_{i,j}$ represents the port on the i^{th}-joint through which the cable that guides the j^{th}-joint passes, an example of the routing on 1^{st}-joint is shown in Fig. 2.

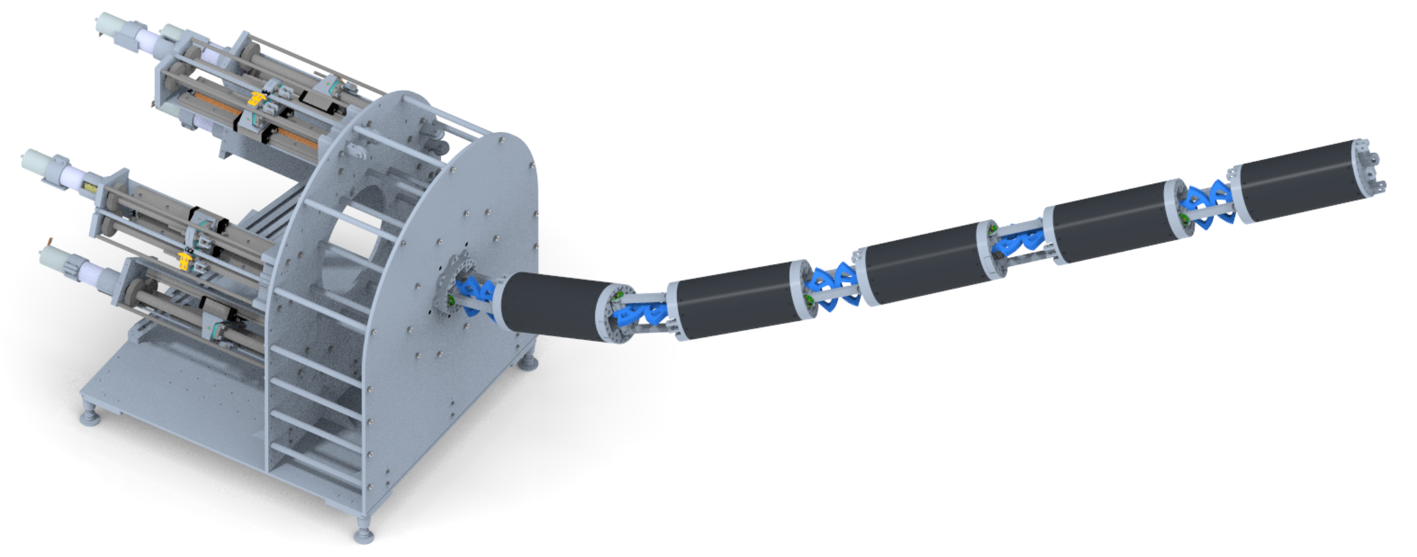


Fig. 1 Cable-driven fully-actuated robot with 5 DoFs

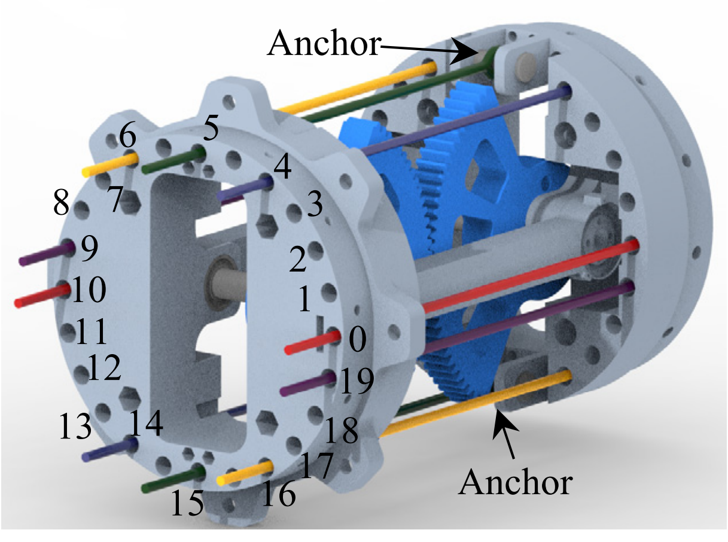


Fig. 2 Example of the cable routing on the 1^{st}-joint of the robot

$$\mathbf{T} = \begin{bmatrix} t_{1,1} & t_{1,2} & t_{1,3} & t_{1,4} & t_{1,5} \\ 0 & t_{2,2} & t_{2,3} & t_{2,4} & t_{2,5} \\ 0 & 0 & t_{3,3} & t_{3,4} & t_{3,5} \\ 0 & 0 & 0 & t_{4,4} & t_{4,5} \\ 0 & 0 & 0 & 0 & t_{5,5} \end{bmatrix}$$

Objectives

This work aims to find the optimal matrix **T** which:

- Reduces the **cable loads**
- Reduces the required **range of motion** (RoM) of the actuators

using **modeFRONTIER**.

Methodology

T

Design rules:

- $t_{i,i} = 5$
- $t_{i,i+1} = 0$ or 10

6 optimization variables

Γ

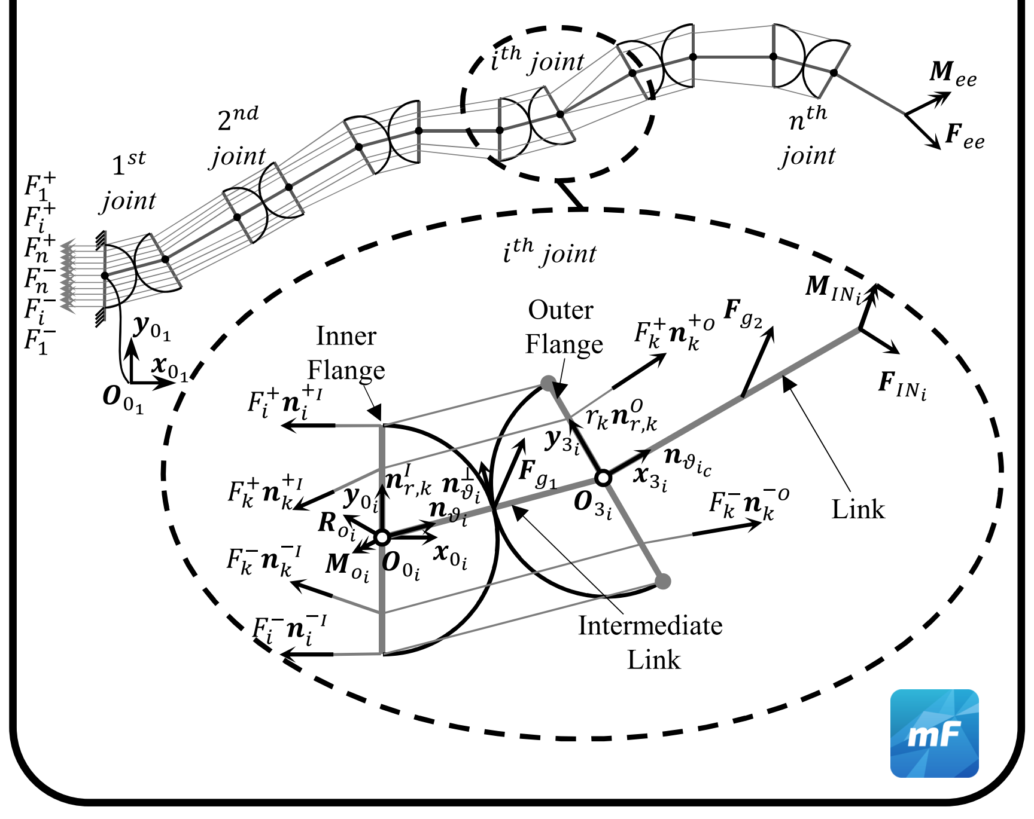
Constraints:

- $t_{i,j} \neq t_{i,k}$
- $t_{i,j} \neq t_{i,k}+10$
- cable intersections with i<j<n, j≠k

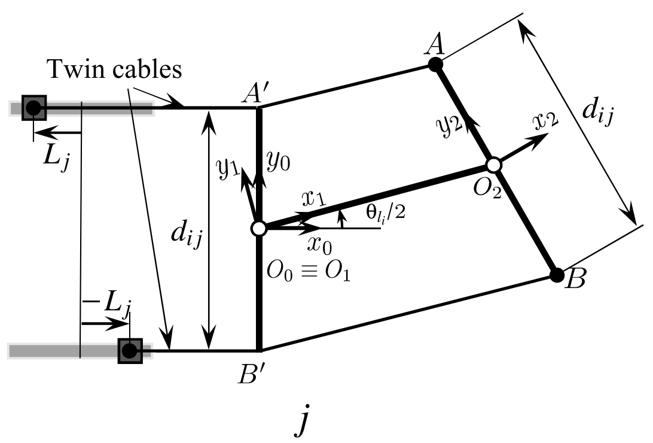
Inner Optimization

Max Cable Forces

$$F_{c_i} = F_0 + \frac{1}{2}\max_{\theta} \quad \left|\Delta F_i\left(\theta, \mathbf{T}, \mathbf{F}_i^n\right)\right|$$
$$\text{s.t.} \quad \left|\theta_j\right| < \theta_l \qquad j = 1\ldots n$$



Max Actuator RoM



$$L_{j_{max}} = \sum_{i=1}^{j} \left|d_{ij}\sin\theta_{l_i}\right|$$

Outer Optimization

1st Example

$$\min_{\mathbf{T}\in\Gamma}\left(F_{c_1},\ldots,F_{c_{n-2}}\right)$$

Minimization of the maximum cable forces.

2nd Example

$$\min_{\mathbf{T}\in\Gamma}\left(\left\|\mathbf{F}_0^{n-2}\right\|_2, \left\|\mathbf{L}_{max}\right\|_2\right)$$

Minimization of the maximum cable forces and the required actuator range of motion

Optimization parameters:

- Algorithm: MOGA II
- Number of generation: 20
- Initial population: 60

Results

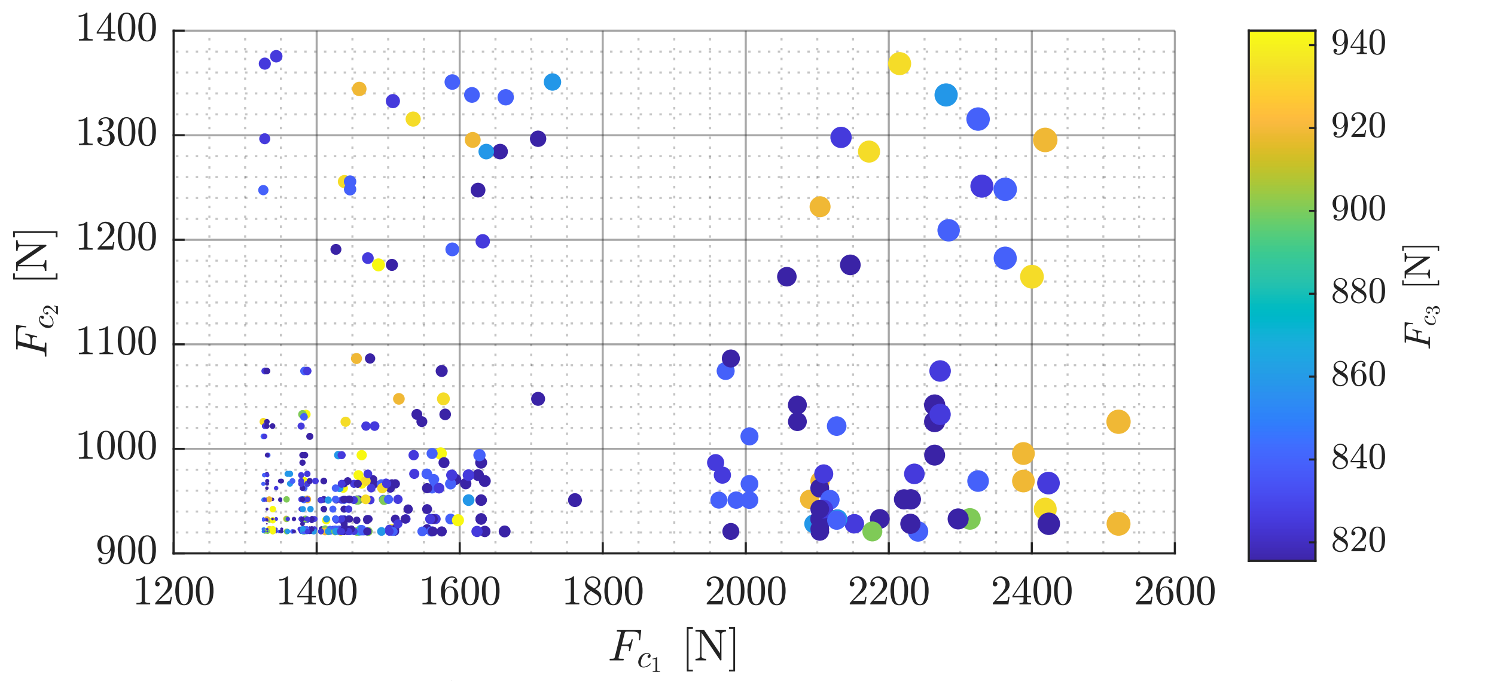


Fig. 3 Results of the 1^{st} example, the size of the marker is proportional to $\left\|\mathbf{F}_0^n\right\|_2$

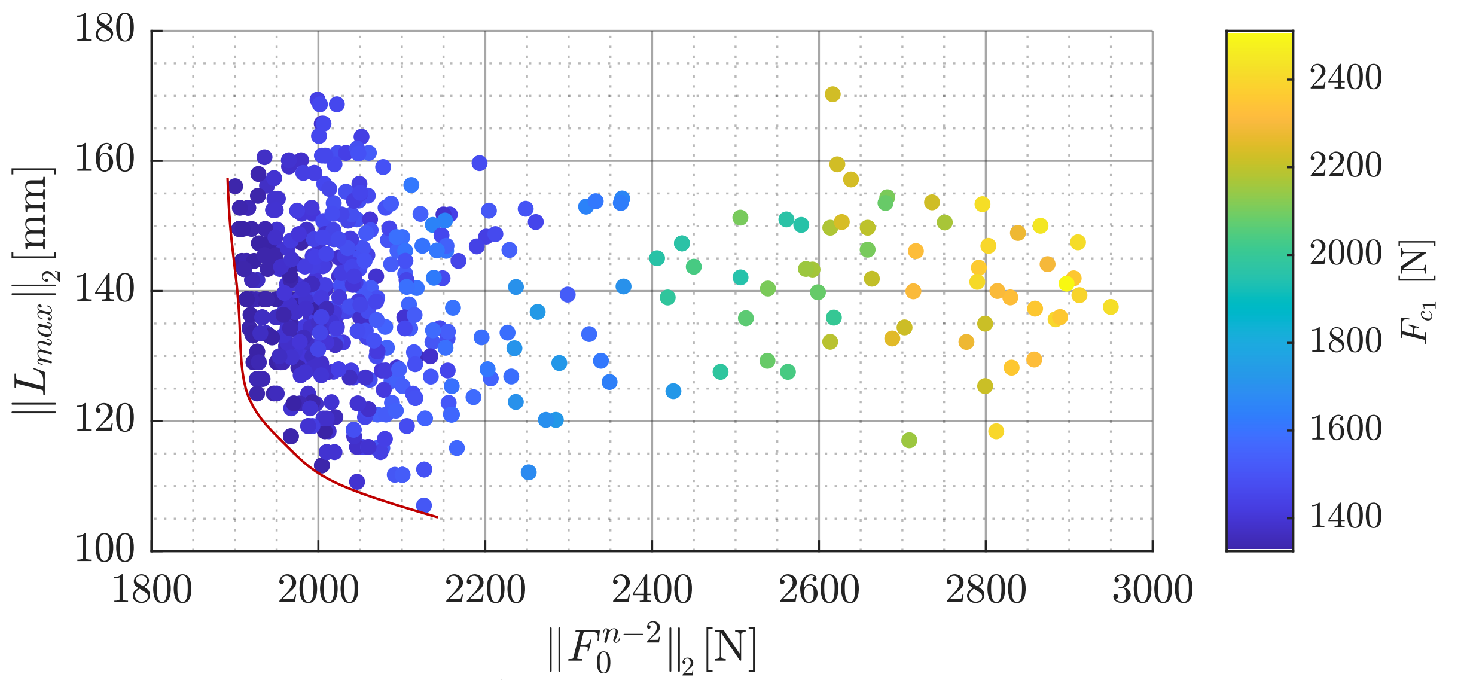


Fig. 4 Results of the 2^{nd} example, the red line represents the Pareto front

	Example 1	Example 2	u.m.
F_{c_1}	1330	1334	[N]
F_{c_2}	921	1048	[N]
F_{c_3}	816	901	[N]
$\left\|\mathbf{F}_0^{n-2}\right\|_2$	1900	2004	[N]
$\left\|\mathbf{L}_{max}\right\|_2$	156	113	[mm]

Table 1 Summary of the optimization results

Conclusion

With respect to a user-defined cable routing matrix, the two different optimization examples reduce:

- **Max cable forces**: F_{c1}, F_{c2} and F_{c3} respectively by **44%**, **26%** and **2%**
- **Max actuator RoM**: L_{3max}, L_{4max} and L_{5max} respectively by **3%**, **27%** and **31%**

The percentage frequency of the components of matrix **T** are reported in Fig. 5.

The results show a tendency of the algorithm to concentrate the components in certain ports.

In particular:

- $t_{1,3}$ is mainly concentrated in port 4
- $t_{1,5}$ is mainly concentrated in port 6
- $t_{2,4}$ is mostly distributed in ports 4 and 6
- $t_{i,i+2k}$ with k = 1, …, n-2-i as close as possible to the port aligned with the anchor point of the i^{th}-joint

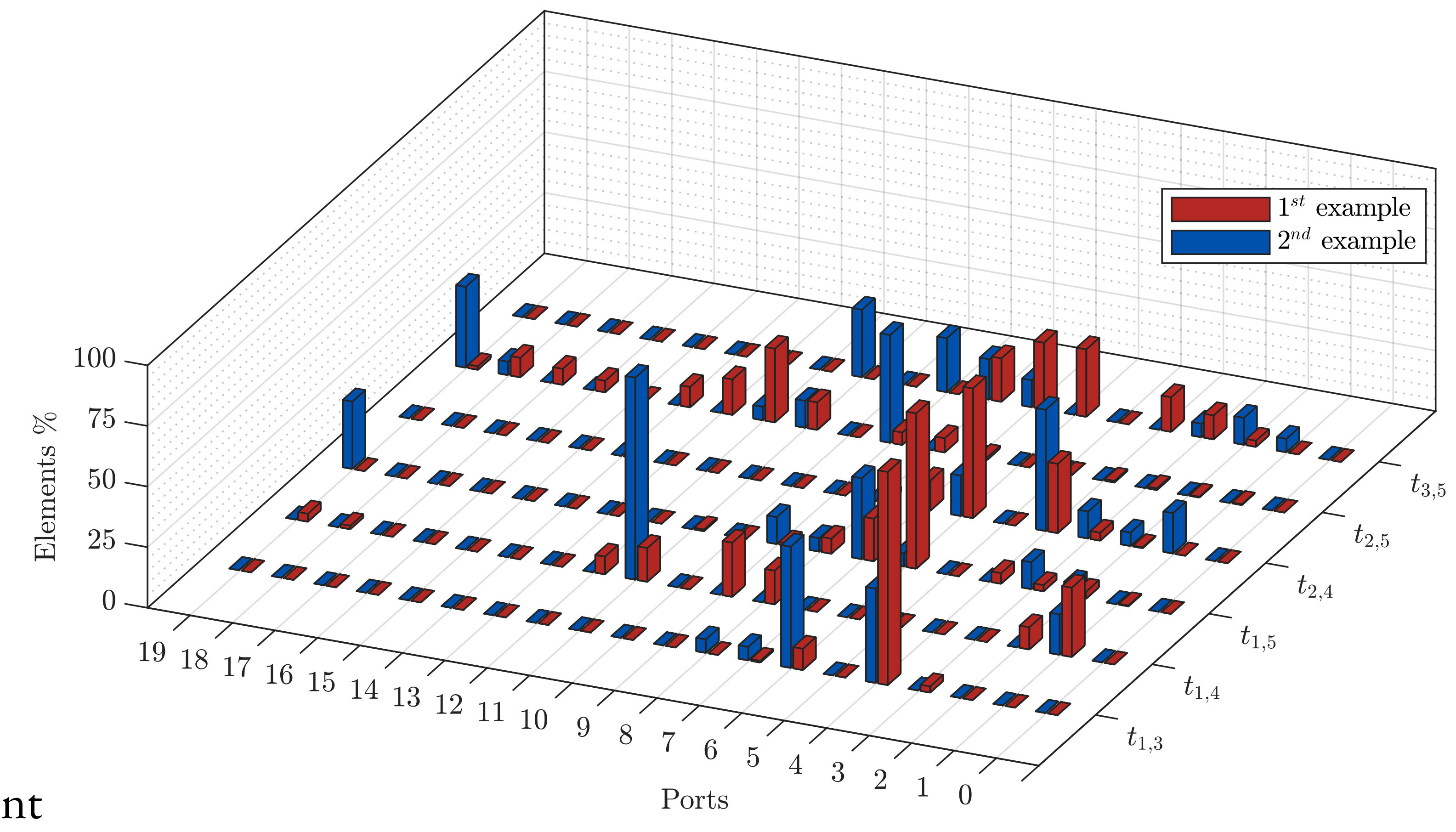


Fig. 5 Distribution of the elements of the cable routing matrix **T** for the two examples

References

[1] Guardiani, Paolo, et al. "Design and Analysis of a Fully Actuated Cable-Driven Joint for Hyper-Redundant Robots with Optimal Cable Routing." Journal of Mechanisms and Robotics (2021): 1-13.

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