Detection and Management of Human-Cable Collision in Cable-Driven Parallel Robots

Presentation for Journée GdR TS4

Hanbang Gao, Christine Chevallereau, and Stéphane Caro

31/01/2025

Nantes Université, École Centrale Nantes, CNRS, LS2N, UMR 6004, F-44000 Nantes, France.
{hanbang.gao, christine.chevallereau, stephane.caro}@ls2n.fr

H. Gao, C. Chevallereau and S. Caro, "Detection and Management of Human-Cable Collision in Cable-Driven Parallel Robots," in IEEE Robotics and Automation Letters, vol. 9, no. 12, pp. 11698-11705, Dec. 2024, doi: 10.1109/LRA.2024.3487051.
H. Gao, C. Chevallereau and S. Caro, "Advancements in Human-Cable Collision Detection and Management in Cable-Driven Parallel Robots," in Proceedings of the Seventh International Conference on Cable-Driven Parallel Robots, Hong Kong, China, July 8-11, 2025. Under review.

Table of contents

Introduction

Collaborative Cable-Driven Parallel Robots

Cable-Driven Parallel Robots (CDPRs) are commonly used for **streaming** in entertainment and sports events.

In **factories**, CDPRs can be used for spraying, transporting, and nailing tasks [1].

Cable-Driven Parallel Robots (CDPRs) are commonly used for **streaming** in entertainment and sports events.

In **factories**, CDPRs can be used for spraying, transporting, and nailing tasks [1].

For high-level collaborative tasks, CDPRs and human operators share the **same workspace** and have physical interaction [2, 3].

Main Contribution

Our research introduces a novel and comprehensive **framework** that integrates collision detection, cable identification, management, and post-collision recovery. Each phase of this framework has been validated through comprehensive experiments.

Main Contribution

Our research introduces a novel and comprehensive **framework** that integrates collision detection, cable identification, management, and post-collision recovery. Each phase of this framework has been validated through comprehensive experiments.

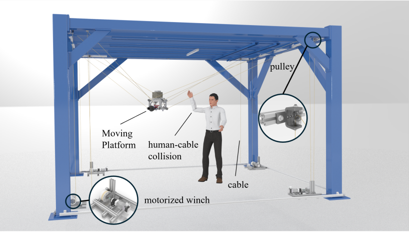

Figure 1: CRAFT prototype in LS2N, Nantes, and human-cable collision schematic diagram

The sensors used in all experiments are dynamometers measuring **cable tensions** $\boldsymbol{\tau}_m$ and motor encoders measuring **joint angles** $\boldsymbol{q}_m$ at a frequency of 1000 Hz.

Main Contribution

Our research introduces a novel and comprehensive **framework** that integrates collision detection, cable identification, management, and post-collision recovery. Each phase of this framework has been validated through comprehensive experiments.

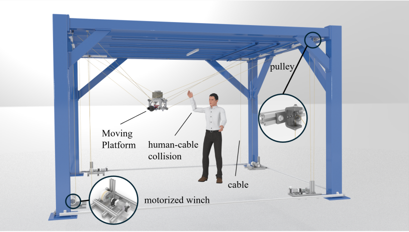

Figure 1: CRAFT prototype in LS2N, Nantes, and human-cable collision schematic diagram

The sensors used in all experiments are dynamometers measuring **cable tensions** $\boldsymbol{\tau}_m$ and motor encoders measuring **joint angles** $\boldsymbol{q}_m$ at a frequency of 1000 Hz.

Safety Issue

- The small diameter of cables exerts high **pressure** at the contact point, posing potential risks to operators [4], and the maximum admissible contact force is **20 N**.
- There's a significant gap in handling **human-cable collisions** in CDPRs without prior knowledge.
- The strategy reduces colliding cable tension to prevent operator injury, achievable by modulating tensions via the tension distribution algorithm when properly positioned in the workspace.

Collision Detection

Methodology

- Human-cable proximity can be monitored by motion capture systems or capacitive cables [5], which have limitations.
- **Cable tension sensors** are straightforward to install and versatile in application.
- It is assumed that only one cable collision occurs at a time. The cable is considered **massless** and **elastic**.

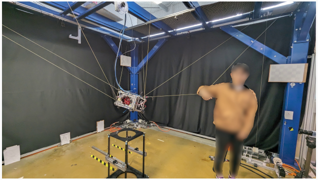

Figure 2: Human-cable collision experiment

Methodology

- Human-cable proximity can be monitored by motion capture systems or capacitive cables [5], which have limitations.
- **Cable tension sensors** are straightforward to install and versatile in application.
- It is assumed that only one cable collision occurs at a time. The cable is considered **massless** and **elastic**.

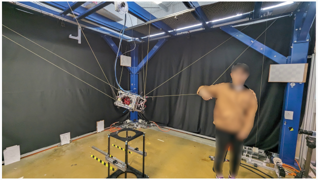

Figure 2: Human-cable collision experiment

Collision Condition:

$$\exists\, \delta\tau_i \in \boldsymbol{\delta\tau} : \delta\tau_i > T_h$$

Threshold $T_h = 3\,\mathrm{N}$, $\boldsymbol{\delta\tau} = \boldsymbol{\tau}_{mf} - \boldsymbol{\tau}_d$.

Collision Detection

Methodology

- Human-cable proximity can be monitored by motion capture systems or capacitive cables [5], which have limitations.
- **Cable tension sensors** are straightforward to install and versatile in application.
- It is assumed that only one cable collision occurs at a time. The cable is considered **massless** and **elastic**.

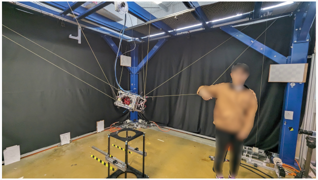

Figure 2: Human-cable collision experiment

Collision Condition:

$$\exists\, \delta\tau_i \in \boldsymbol{\delta\tau} : \delta\tau_i > T_h$$

Threshold $T_h = 3\,\mathrm{N}$, $\boldsymbol{\delta\tau} = \boldsymbol{\tau}_{mf} - \boldsymbol{\tau}_d$.

Results

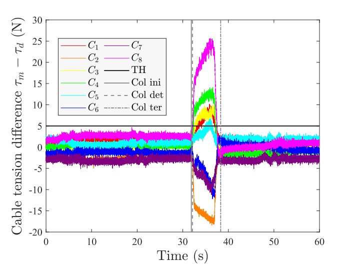

Figure 3: Difference between measured and desired cable tensions during a collision event

- Short detection interval: 0.225 s.
- Analysis of tension errors.

Cable Collision Identification: Problem and Case

Problem Statement

- **Objective**: Identify the specific cable involved in a collision as it occurs.
- Collisions cause variations in **all** cable tensions.

Cable Collision Identification: Problem and Case

Problem Statement

- **Objective**: Identify the specific cable involved in a collision as it occurs.
- Collisions cause variations in **all** cable tensions.

Heuristic Method

- Assumes the cable with the highest tension difference ($\delta\tau$) is the collided cable.
- May misidentify the collided cable, especially when diagonal cables are involved.

Problem Statement

- **Objective**: Identify the specific cable involved in a collision as it occurs.
- Collisions cause variations in **all** cable tensions.

Heuristic Method

- Assumes the cable with the highest tension difference ($\delta\tau$) is the collided cable.
- May misidentify the collided cable, especially when diagonal cables are involved.

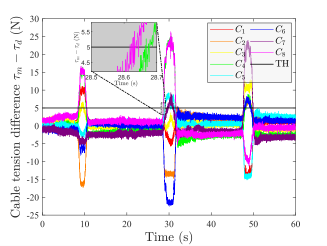

Figure 4: Difference between measured and desired cable tensions during collisions with Cable 8, Cable 4, and Cable 7.

Results: Collision with Cable 4 could be incorrectly identified as Cable 8.

Cable Collision Identification: Problem and Case

Problem Statement

- **Objective**: Identify the specific cable involved in a collision as it occurs.
- Collisions cause variations in **all** cable tensions.

Heuristic Method

- Assumes the cable with the highest tension difference ($\delta\tau$) is the collided cable.
- May misidentify the collided cable, especially when diagonal cables are involved.

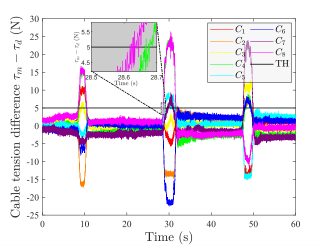

Figure 4: Difference between measured and desired cable tensions during collisions with Cable 8, Cable 4, and Cable 7.

Results: Collision with Cable 4 could be incorrectly identified as Cable 8.

Identification Criteria

- **Assumption 1**: Collision causes a shape change in the impacted cable, affecting its force direction.
- **Assumption 2**: The system remains controllable and stable; the moving platform (MP) maintains its trajectory.

Configure Estimation Function $g(x)$

$$g(x) = \left| \left| \sum_{i=1,\, i \neq x}^{8} \mathbf{u}_{id}^{T} \delta\tau_i \right| - |\delta\tau_x| \right|$$

- The collided index minimizes $g(x)$.

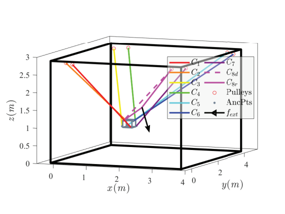

Figure 5: Geometry effects due to collision between Cable 8 and the environment.

- Platform equilibrium is represented by the equation $\mathbf{u}\delta\tau$, and for the colliding cable, $u_n \neq u_{nd}$ serves as the criterion.

Configure Estimation Function $g(x)$

$$g(x) = \left| \left| \sum_{i=1,\, i \neq x}^{8} \mathbf{u}_{id}^{T} \delta\tau_i \right| - |\delta\tau_x| \right|$$

- The collided index minimizes $g(x)$.

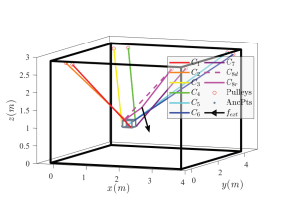

Figure 5: Geometry effects due to collision between Cable 8 and the environment.

- Platform equilibrium is represented by the equation $\mathbf{u}\delta\tau$, and for the colliding cable, $u_n \neq u_{nd}$ serves as the criterion.

Results and Analysis

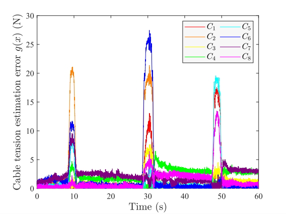

Figure 6: Estimated tension errors $g(x)$ for all cables during collision events.

Configure Estimation Function $g(x)$

$$g(x) = \left| \left| \sum_{i=1,\, i \neq x}^{8} \mathbf{u}_{id}^{T} \delta\tau_i \right| - |\delta\tau_x| \right|$$

- The collided index minimizes $g(x)$.

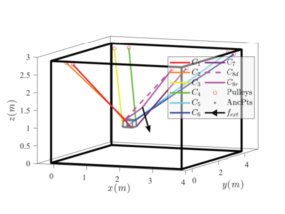

Figure 5: Geometry effects due to collision between Cable 8 and the environment.

- Platform equilibrium is represented by the equation $\mathbf{u}\delta\tau$, and for the colliding cable, $u_n \neq u_{nd}$ serves as the criterion.

Results and Analysis

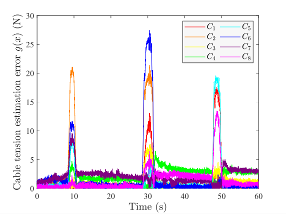

Figure 6: Estimated tension errors $g(x)$ for all cables during collision events.

Sequence	Largest $\delta\tau$	Smallest $g(x)$	Identified Cable
1st Collision	$C_8 > C_4$	$C_8 < C_1$	C_8
2nd Collision	$C_8 > C_4$	$C_4 < C_5$	C_4
3rd Collision	$C_7 > C_3$	$C_7 < C_6$	C_7

Collision Management

Collision Management: Objective and Methodology

Collision Management Strategies

- **Objective**: Reduce tension in the collided cable to a minimum to prevent injury risk.
- **Assumption**: The strategy is applied within restrained feasible workspace.
- **Restrained Feasible Workspace**: Pose can be maintained with zero tension in the collided cable.
- **Methodology**: The proposed strategy reduces the desired cable tension using a tension distribution algorithm, blocks joint correction, and simultaneously increases the length of the collided cable to induce sagging. To ensure effectiveness, closed-loop cable tension tracking is employed.

Collision Management: Objective and Methodology

Collision Management Strategies

- **Objective**: Reduce tension in the collided cable to a minimum to prevent injury risk.
- **Assumption**: The strategy is applied within restrained feasible workspace.
- **Restrained Feasible Workspace**: Pose can be maintained with zero tension in the collided cable.
- **Methodology**: The proposed strategy reduces the desired cable tension using a tension distribution algorithm, blocks joint correction, and simultaneously increases the length of the collided cable to induce sagging. To ensure effectiveness, closed-loop cable tension tracking is employed.

Adaptive Cable Release Method

- **Objective**: Joint position control is applied to the other seven cables to maintain system position, while tension control is applied to the collided cable to track the minimum desired tension τ_{dmin}. The desired elongation of cable should be:

$$\delta l_c = K_g T_s \,\mathrm{sgn}_m(\delta\tau_f) + K_e T_s \,\delta\tau_f, \tag{1}$$

T_s is the system frequency and sgn_m is the modified sign function. The definition of the tracking error is $\delta\tau_f = \tau_{mf} - \tau_{dmin}$.

Collision Management: Objective and Methodology

Collision Management Strategies

- **Objective**: Reduce tension in the collided cable to a minimum to prevent injury risk.
- **Assumption**: The strategy is applied within restrained feasible workspace.
- **Restrained Feasible Workspace**: Pose can be maintained with zero tension in the collided cable.
- **Methodology**: The proposed strategy reduces the desired cable tension using a tension distribution algorithm, blocks joint correction, and simultaneously increases the length of the collided cable to induce sagging. To ensure effectiveness, closed-loop cable tension tracking is employed.

Adaptive Cable Release Method

- **Objective**: Joint position control is applied to the other seven cables to maintain system position, while tension control is applied to the collided cable to track the minimum desired tension τ_{dmin}. The desired elongation of cable should be:

$$\delta l_c = K_g T_s \operatorname{sgn}_m(\delta\tau_f) + K_e T_s \, \delta\tau_f, \qquad (1)$$

T_s is the system frequency and sgn_m is the modified sign function. The definition of the tracking error is $\delta\tau_f = \tau_{mf} - \tau_{dmin}$.

Methodology Overview

- Collision Detection and Initial Response
- Gradual Tension Reduction
- Tension and Length Restoration

Management for Human-Cable Collisions

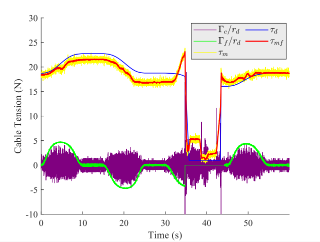

Figure 7: Cable 7 tension and collision response with the proposed strategy

- Upon collision detection, the measured cable tension was reduced to less than 5 N and the friction compensation was blocked.
- The collided cable tension decreases upon collision detection happening within 1 s.

Management for Human-Cable Collisions

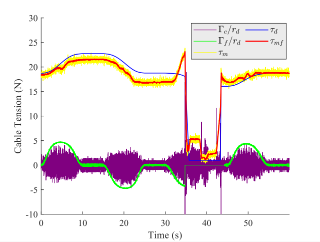

Figure 7: Cable 7 tension and collision response with the proposed strategy

- Upon collision detection, the measured cable tension was reduced to less than 5 N and the friction compensation was blocked.
- The collided cable tension decreases upon collision detection happening within 1 s.

Collision End Detection

- Reference tensions $\boldsymbol{\tau}_d$ are unreliable post-collision due to adjustments during management.
- Collision is considered ended when δl_c to remain below 0.1 mm for 1 second.

Management for Human-Cable Collisions

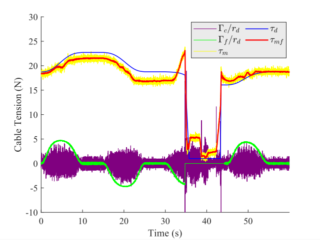

Figure 7: Cable 7 tension and collision response with the proposed strategy

- Upon collision detection, the measured cable tension was reduced to less than 5 N and the friction compensation was blocked.
- The collided cable tension decreases upon collision detection happening within 1 s.

Collision End Detection

- Reference tensions $\boldsymbol{\tau}_d$ are unreliable post-collision due to adjustments during management.
- Collision is considered ended when δl_c to remain below 0.1 mm for 1 second.

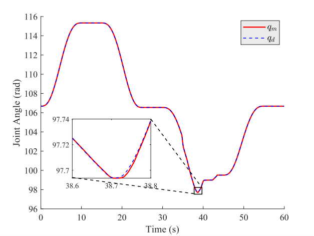

Figure 8: Desired and measured motor joint angles ($\mathbf{q}_d$ and $\mathbf{q}_m$)

The restoration of the cable tension and length takes 2 s.

Experimental Results Video

Click here to play the video

Conclusion

Summary and Future Work

Main Contributions

- **Collision Detection**: Presented two distinct methodologies for collision detection and collision end detection in CDPRs.
- **Cable Collision Identification**: Addressed the challenge of determining the collided cable and proposed a mathematical model utilizing measured and desired cable tensions.
- **Collision Management**: Detailed management strategies for effectively addressing both minor and severe collisions.

Future Work

- **Manage collisions outside the feasible workspace using escape trajectories**.
- Extend methods to human-platform, cable-cable collisions and cable breakage.
- Develop collision models for accurately reconstructing collision scenarios.
- Enhance safety and efficiency measures for CDPRs in collaborative environments.

Questions?

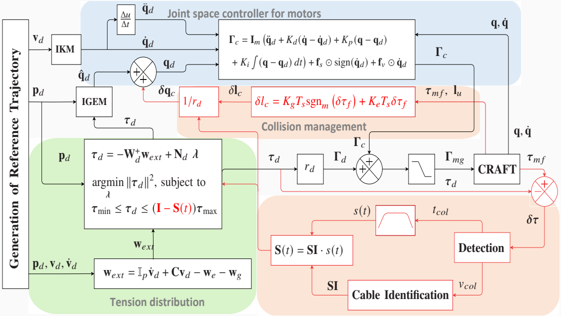

Figure 9: Control scheme of the CRAFT platform: black components represent the standard control scheme, while red components introduce collision management Strategy.

Variable Nomenclature

$\mathbf{q}_m$: Measured joint angles $\mathbf{q}_d$: Desired joint angles
$\boldsymbol{\tau}_m$: Filtered measured cable tensions
$\boldsymbol{\tau}_d$: Desired cable tensions $\mathbf{f}_s/\mathbf{f}_v$: Static/Fluid friction
$\boldsymbol{\Gamma}_{mg}$: Output motor torques

Management Procedures

- Upon collision detection, $\mathbf{v}_{col}$ records the collision tension profile, and $s(t)$ gradually reduces tension over 2 seconds, with **SI** identifying the impacted cable.
- The management function $\mathbf{S}(t)$ lowers $\boldsymbol{\tau}_{\max}$ to $\boldsymbol{\tau}_{\min}$ while gradually adapting motor angle $\mathbf{q}_d$.
- After collision resolution, $\mathbf{S}(t)$ restores $\boldsymbol{\tau}_{\max}$ and $\mathbf{q}_d$ to nominal values smoothly.

References i

- S. Qian, B. Zi, W.-W. Shang, and Q.-S. Xu, “A review on cable-driven parallel robots,” *Chinese Journal of Mechanical Engineering*, vol. 31, no. 1, pp. 1–11, 2018.
- J. Garrido, D. Silva-Muñiz, E. Riveiro, J. Rivera-Andrade, and J. Sáez, “Collaborative behavior for non-conventional custom-made robotics: A cable-driven parallel robot application,” *Machines*, vol. 12, no. 2, p. 91, 2024.
- M. Métillon, C. Charron, K. Subrin, and S. Caro, “Performance and interaction quality variations of a collaborative cable-driven parallel robot,” *Mechatronics*, vol. 86, p. 102839, 2022.
- T. Rousseau, C. Chevallereau, and S. Caro, “Human-cable collision detection with a cable-driven parallel robot,” *Mechatronics*, vol. 86, p. 102850, 2022.
- M. Métillon, L. Rasolofondraibe, R. Gayol, L. Contal, S. Acoulon, C. Charron, K. Subrin, and S. Caro, “A capacitive cable-based detection device for cable-driven parallel robots,” Poster presented at CableCon 2023, Nantes, France, June 25-28 2023.