



Nantes
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Laboratoire des Sciences
du Numérique de Nantes



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

Presentation for ICRA 2025

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1. Introduction
2. Collision Detection
3. Collision Management
4. Conclusion

Introduction

The Collaborative Robots



Figure 1: Industry 4.0 [1]



Figure 2: Underwater Robots [2]



Figure 3: Wearable robotics [3]

The Collaborative Robots



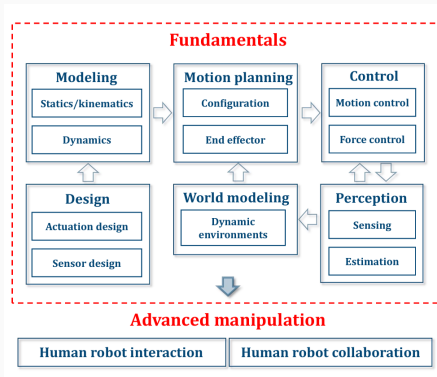
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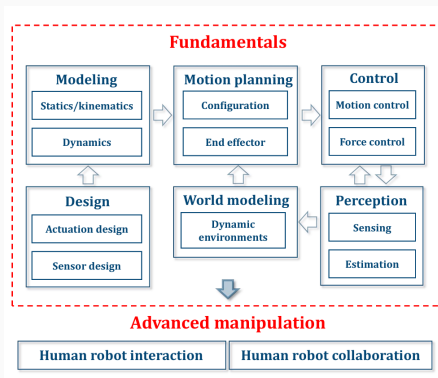
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Enhance Productivity

Mitigate Risks

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

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For high-level collaborative tasks, CDPRs and human operators share the same workspace and have physical interaction [5, 6].

Safety Issue

- According to [7], the small diameter of cables exerts high pressure at the contact point, posing potential risks to operators.
- The maximum admissible contact force is 20 N.

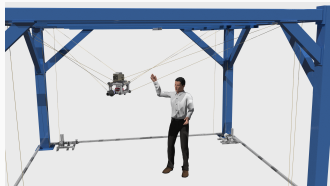


Figure 4: Collision between a hand and a cable
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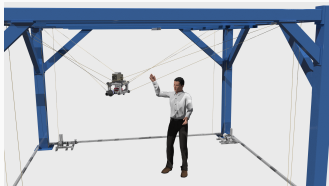


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Research Gap

- Most existing research focuses on **avoidance strategies** for human-cable collisions [8, 9, 10].
- Studies address self-interference like cable-cable and cable-object collisions [11, 12, 13].
- Issues related to known collision obstacles are explored in [13, 14, 15].
- Deploying CDPRs in complex environments where cable collisions are inevitable is discussed in [16].

However, there's a significant gap in handling **human-cable collisions** in autonomous systems without prior knowledge of potential collision situations.

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.

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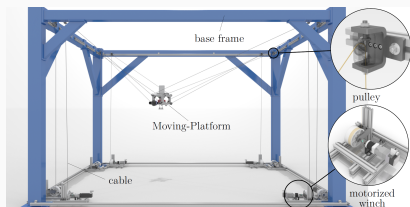


Figure 5: The CRAFT platform in LS2N, Nantes.

The sensors used in all experiments are dynamometers measuring **cable tensions** τ_m and motor encoders measuring **joint angles** q_m at a frequency of 1000 Hz.

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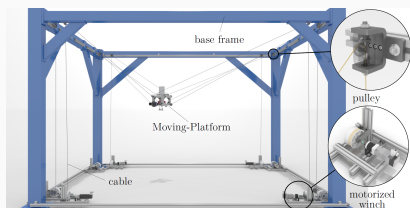


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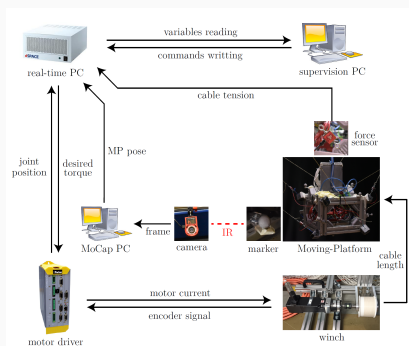


Figure 6: Components, Sensors and Communication Structure of the CRAFT

Control scheme of the CRAFT platform

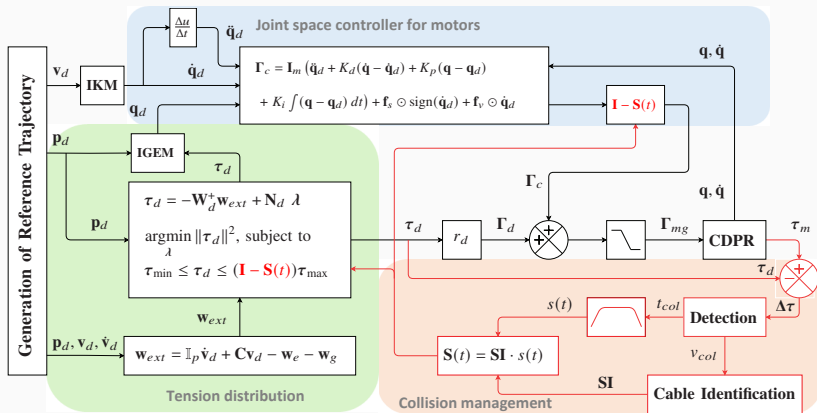


Figure 7: Control scheme of the CRAFT platform: the black components represent the standard operational control scheme without collision management. The red components introduce the collision management Strategy 1.

Variable Nomenclature

\mathbf{q}_m Measured joint angles \mathbf{q}_d Desired joint angles τ_m Measured cable tensions
 τ_d Desired cable tensions $\mathbf{f}_s/\mathbf{f}_v$ Static/Fluid friction Γ_{mg} Output motor torques

Collision Detection

Methodology

- Human-cable proximity can be monitored by motion capture systems or capacitive cables [17], 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**.

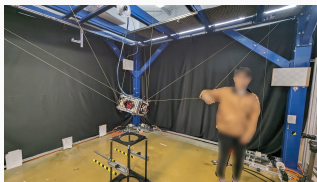


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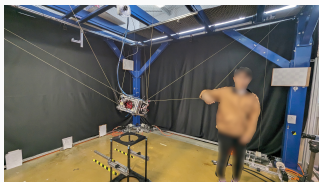


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Collision Condition:

$$\exists \Delta\tau_i \in \Delta\tau : \Delta\tau_i > T_h$$

Threshold $T_h = 5 \text{ N}$, $\Delta\tau = \tau_m - \tau_d$.

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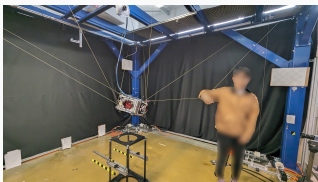


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Results

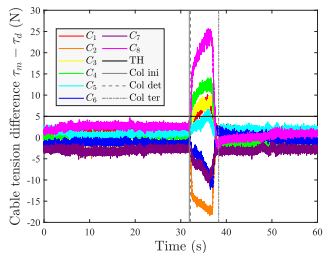


Figure 9: Difference between measured and desired cable tensions during a collision event

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

Problem Statement

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

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- 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.

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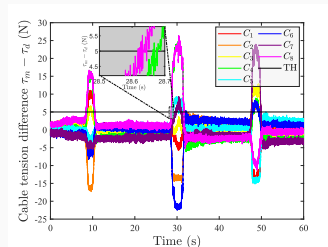


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Results: Collision with Cable 4 could be incorrectly identified as Cable 8.

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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.

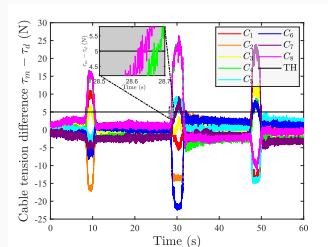


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$$g(x) = \left| \left| \sum_{i=1, i \neq x}^8 \mathbf{u}_{id}^T \Delta \tau_i \right| - |\Delta \tau_x| \right|$$

- \mathbf{u}_{id} is the desired unit vector of Cable i .
- The collided cable index minimizes $g(x)$.

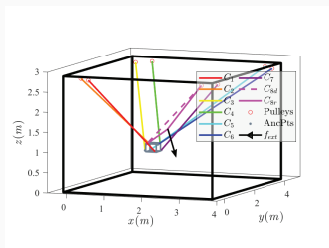


Figure 11: Geometry effects due to collision between Cable 8 and the environment.

Cable Collision Identification: Method and Results

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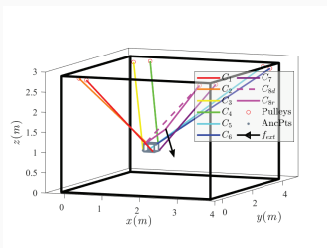


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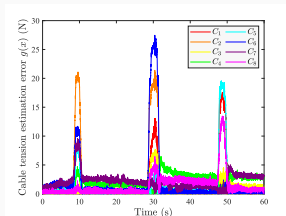


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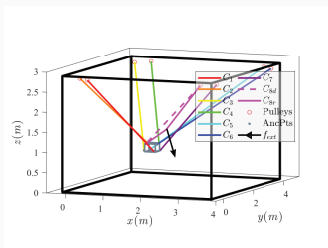


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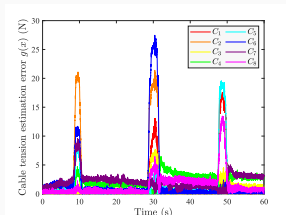


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Sequence	Largest $\Delta \tau$	Smallest $g(x)$	Identified Cable
1 st Collision	$C_8 > C_4$	$C_8 < C_1$	C_8
2 nd Collision	$C_8 > C_4$	$C_4 < C_5$	C_4
3 rd Collision	$C_7 > C_3$	$C_7 < C_6$	C_7

Collision Management

Collision Force Calculation

Equivalent force acting on the MP:

$$\mathbf{f}_{eq} = \begin{cases} \mathbf{U}_d \Delta \boldsymbol{\tau}, & \text{if no collision} \\ \sum_{j=1, j \neq c}^8 \mathbf{u}_{jd} \Delta \tau_j, & \text{if cable } c \text{ collides} \end{cases}$$

Terms for the collided cable are excluded to reduce error.

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Collision Classification

- **Restrained Feasible Workspace:** Pose can be maintained with zero tension in the collided cable.
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Collision Management Strategies

- **Objective:** Reduce tension in the collided cable to a minimum to prevent injury risk.
- **Assumption:** The strategies are applied within restrained feasible workspace.
- **Difference:** Strategy 1 reduces cable tension using a **tension distribution algorithm**, whereas Strategy 2 also increases the length of the collided cable to induce **sagging**. This second approach requires more time for restoration after the collision ends.

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Methodology Overview

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

Control Scheme and Management Procedures

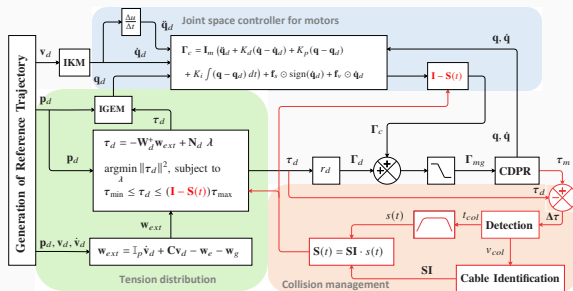


Figure 13: Control scheme of the CRAFT platform: black components represent the standard control scheme, while red components introduce collision management Strategy 1.

Variable Nomenclature

q_m : Measured joint angles q_d : Desired joint angles
 τ_m : Measured cable tensions
 τ_d : Desired cable tensions f_s/f_v : Static/Fluid friction
 Γ_{mg} : Output motor torques

Management Procedures

- Upon collision detection, v_{col} records the collision tension profile, and $s(t)$ gradually reduces tension over 5 seconds, with SI identifying the impacted cable.
- The management function $S(t)$ lowers τ_{max} to τ_{min} while gradually reducing Γ_c to zero.
- After collision resolution, $S(t)$ restores τ_{max} and Γ_c to nominal values smoothly.

Strategy 1 Effective for Minor Collisions

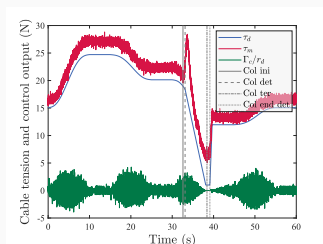


Figure 14: Cable 8 tension and collision response with Strategy 1 for minor collisions.

- At 32.600 s, a collision with Cable 8 is detected, and Collision is confirmed at 33.111 s.
- Measured tension reduces to around 5 N. After collision ends, tension and control output recover.

Collision Management Strategy 1: Results and Limitations

Strategy 1 Effective for Minor Collisions

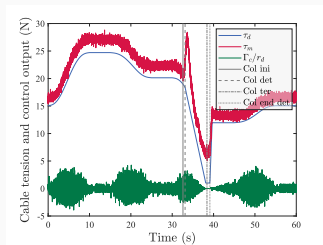


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Ineffective for Severe Collisions

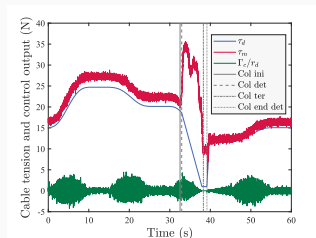


Figure 15: Cable 8 tension and collision response with Strategy 1 for severe collisions.

- Strategy 1 has limitations with ongoing or severe external forces, as tension in the cable rises despite tension reduction efforts.
- Simply reducing desired tension is insufficient.

Cable Elongation Calculation

The optimal extent of cable elongation l_c is calculated as:

$$l_c = \frac{\alpha \tau_{m,c} l_u}{ES}$$

- l_u represents cable lengths from anchor points, ES denotes axial stiffness of the cable and α is a safety factor, chosen as 1.5.

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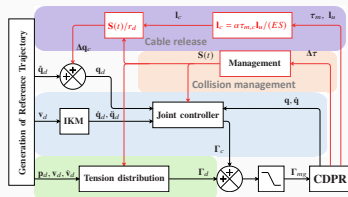


Figure 16: Enhanced control scheme of the CRAFT platform incorporating Strategy 2.

Collision Management Strategy 2: Handling Severe Collisions

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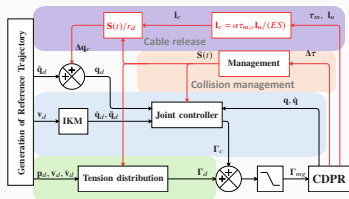


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Results with Strategy 2

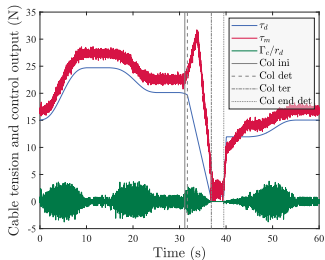


Figure 17: Cable tension and collision response with Strategy 2 for severe collisions.

- Strategy 2 adjusts desired joint positions to reduce tension, which decreases despite severe collision forces.
- Results demonstrates effectiveness in mitigating severe collisions.

Equivalent Force Calculation

The external force \mathbf{f}_{ext} acting on the collided cable is approximated by the equivalent force \mathbf{f}_{eq} exerted on the MP:

$$\mathbf{f}_{\text{eq}} = \begin{cases} \mathbf{U}_d \Delta \boldsymbol{\tau}, & \text{if no collision} \\ \sum_{j=1, j \neq c}^8 \mathbf{u}_{jd} \Delta \boldsymbol{\tau}_j, & \text{if cable } c \text{ collides} \end{cases}$$

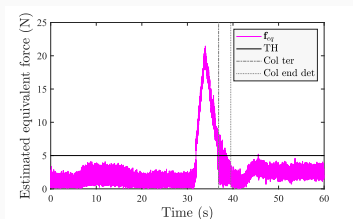


Figure 18: Equivalent force \mathbf{f}_{eq} with the collision management strategy for cable 8. Collision ends around 36.980 s and is detected at 39.503 s.

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Collision End Detection

- Reference tensions τ_d are unreliable post-collision due to adjustments during management.
- Collision is considered ended when $\|\mathbf{f}_{\text{eq}}\|$ remains below 5 N continuously for 1 second.

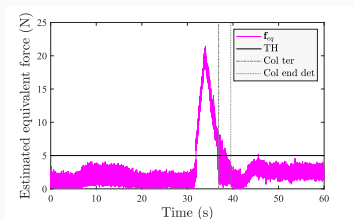


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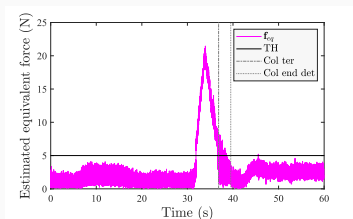


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Restoration Procedure

- Gradually restore desired cable tensions to pre-collision values.
- Unblock PID corrector outputs.
- Adjust desired joint angles (especially when using Strategy 2) to maintain system integrity.
- The order of restoring the desired tension and joint angle affects the results.

[Click here to play the video](#)

Conclusion

Main Contributions







- **Collision Detection:** Presented two distinct methodologies for collision 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 two management strategies for effectively addressing minor and severe collisions.






Future Work

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

Questions?

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