Cable-Driven Parallel Robots for agile operation in manufacturing facilities

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Journée Des Doctorants CETIM 2023
Senlis

17 janvier 2023

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Context

A **Cable-Driven Parallel Robot** (CDPR) consists of a Moving-Platform (MP) connected to a base frame using cables

Drawbacks

- Limited rotations
- Cable collisions

Advantages

- High payload and dynamic capabilities
- Large workspace

Applications

- Handling
- Large-scale 3D printing

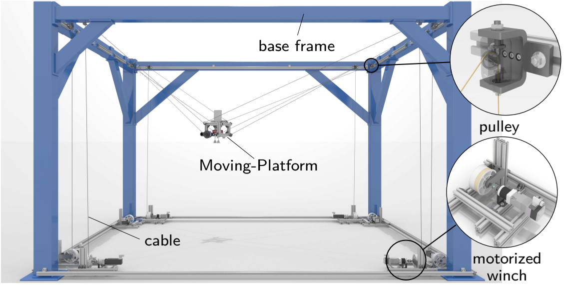


Figure 1: Main components of CRAFT

Cable-Driven Parallel Robots (CDPRs)

Example

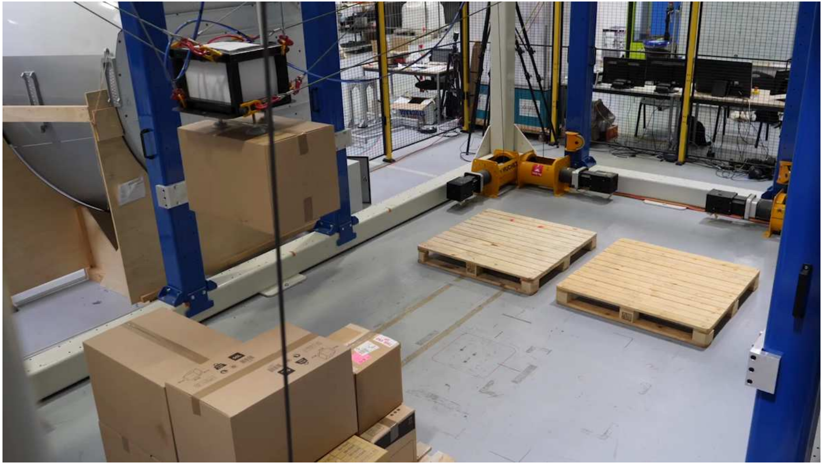


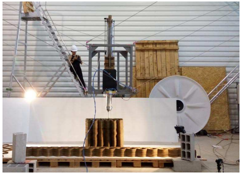
Figure 2: CAROCA prototype, IRT Jules Verne

Cable-Driven Parallel Robots (CDPRs)

Applications

(a) Handling [1]

(b) Assembly [2]



(c) Printing [3]

(d) Heavy payloads [4]

Figure 3: Industrial applications

Context

Goal

Develop agile CDPRs able to safely interact with human users

- Share the workspace with operators
- Physically interact with operators

ANR-CRAFT project consortium

LS2N Inria cetim

Work done

- CDPR elasto-geometric modelling, parametric and sensitivity analysis
- Definition of collaborative control strategies
- User experiment with collaborative CDPRs

Figure 4: Targeted paradigm

Collaborative pick-and-place operations

Paradigm

Task and context

Pick-and-place operation in collaboration

1. Co-existence
2. Collaboration

Goals

1. Evaluate the human robot interaction on a shared task
2. Develop safety strategy
3. Account for CDPR stiffness
4. Enhance transparency

Figure 5: Collaborative pick-and-place paradigm representation

Collaborative pick-and-place operations

CU3 hybrid controller

Reference trajectory

A reference trajectory : $\mathbf{x}_0$, $\mathbf{t}_0$ and $\dot{\mathbf{t}}_0$
Error along the trajectory:

$$\mathbf{e}_x = \mathbf{x}_0 - \mathbf{x} \quad (1)$$

$$\mathbf{e}_t = \mathbf{t}_0 - \mathbf{t} \quad (2)$$

$$\mathbf{e}_{\dot{t}} = \dot{\mathbf{t}}_0 - \dot{\mathbf{t}} \quad (3)$$

Reference trajectory impedance:

$$\mathbf{w}_r = \mathbf{K}_v \mathbf{e}_x + \mathbf{D}_v \mathbf{e}_t + \mathbf{M}_v \mathbf{e}_{\dot{t}} \quad (4)$$

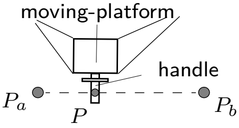


Figure 6: Reference trajectory

Admittance

Human wrench exerted on the handle: $\mathbf{w}_h$

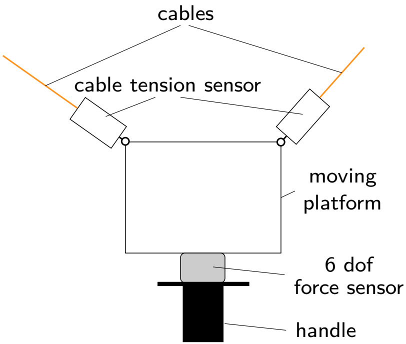


Figure 7: Force sensor of CRAFT

Collaborative pick-and-place operations

Hybrid controller

Reference trajectory

Reference trajectory desired acceleration:

$$\dot{\mathbf{t}}_h = \mathbf{M}_h \mathbf{w}_h \tag{5}$$

Saturation of the acceleration:

$$\dot{\mathbf{t}}_{h/} = \underset{-\alpha\dot{\mathbf{t}}_{max}}{\overset{\alpha\dot{\mathbf{t}}_{max}}{\int}} \dot{\mathbf{t}}_h \tag{6}$$

User admittance

User admittance desired acceleration:

$$\dot{\mathbf{t}}_r = \mathbf{M}_r \mathbf{w}_r \tag{7}$$

Saturation of the acceleration:

$$\dot{\mathbf{t}}_{r/} = \underset{-(1-\alpha)\dot{\mathbf{t}}_{max}}{\overset{(1-\alpha)\dot{\mathbf{t}}_{max}}{\int}} \dot{\mathbf{t}}_r \tag{8}$$

Moving Platfrom desired acceleration

$$\dot{\mathbf{t}}_d = \dot{\mathbf{t}}_{r/} + \dot{\mathbf{t}}_{h/} \tag{9}$$

Collaborative pick-and-place operations

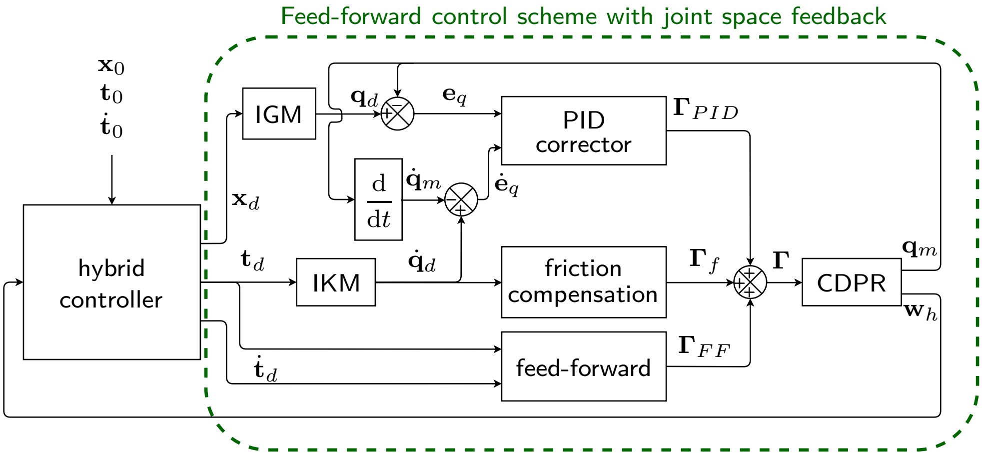


Figure 8: Hybrid control scheme for co-manipulation with a CDPR

Collaborative pick-and-place operations

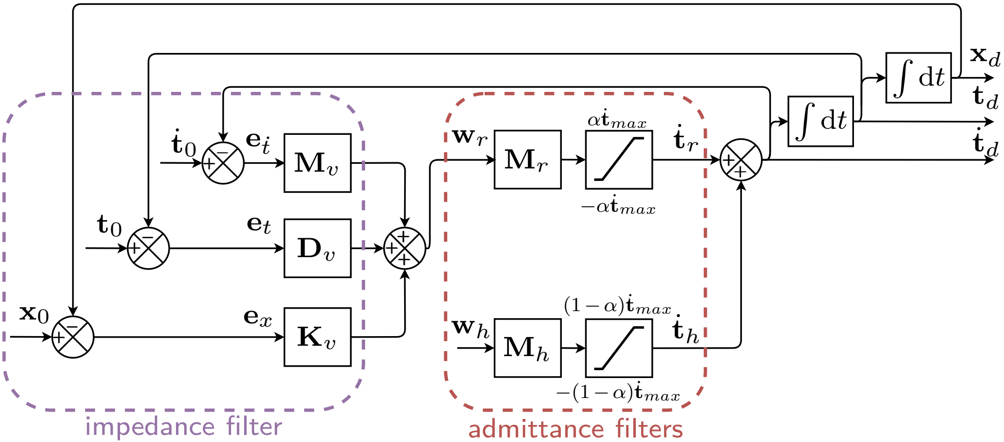


Figure 9: Hybrid control scheme for co-manipulation with a CDPR

Collaborative pick-and-place operations

Compliant trajectory performance

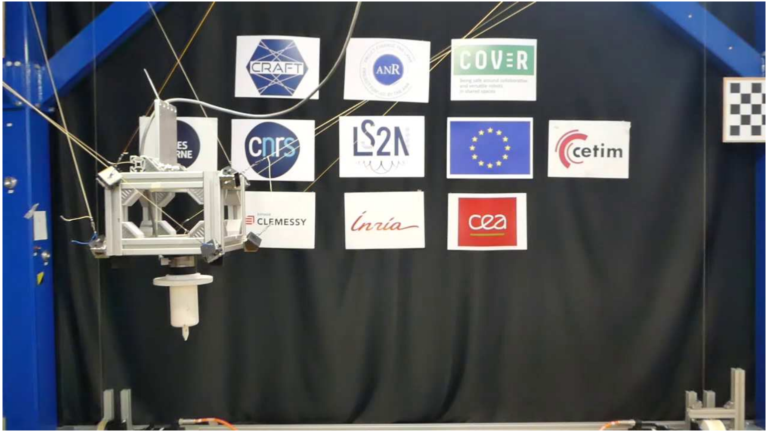


Figure 10: Compliant trajectory performance

Collaborative pick-and-place operations

Interaction during a compliant trajectory

Figure 11: Interaction during a compliant trajectory

Collaborative pick-and-place operations

Interaction with a stiff environment

Figure 12: Interaction with a stiff environment

UC1 : Teleoperation with a suspended 3 cables CDPR

UC1 paradigm

Context

Suspended Cable-Driven Parallel Robot with 3 cables in a teleoperation task

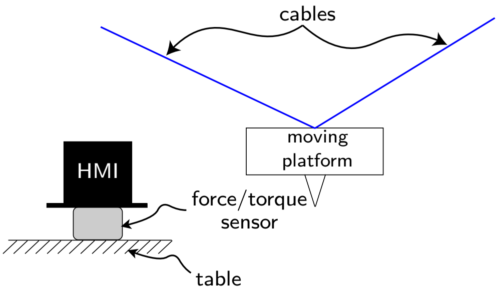


Figure 13: Tele-operated CDPR

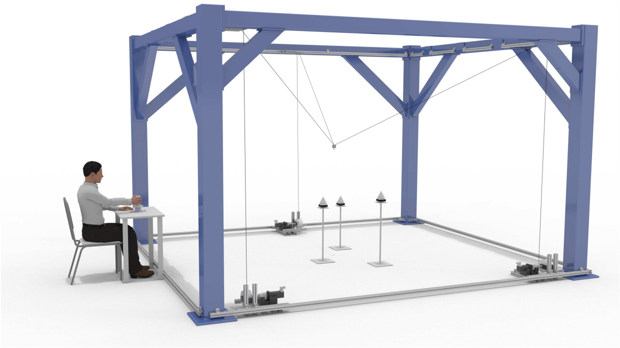


Figure 14: First Use Case (UC1) - Teleoperation of a platform with three cables

UC2 : Comanipulation with a suspended 8 cables CDPR

UC2 paradigm

Context

Suspended Cable-Driven Parallel Robot with 8 cables in a co-manipulation task

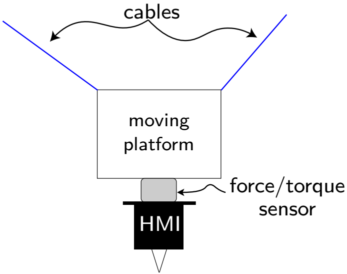


Figure 15: CDPR in co-manipulation

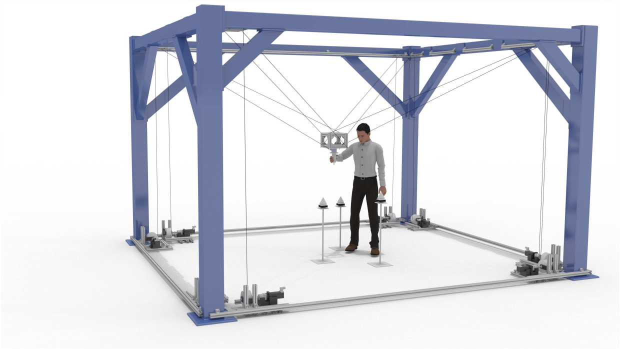


Figure 16: Second Use Case - (UC2) - Co-manipulation of a platform with eight cables

UC1 & UC2 : a comparative user-experiment

Experiment description

Goal

- Compare the user performance on the task completion on both configurations
- Analyse the performance evolution
- Identify performance evolution models

Task

Aiming task with three air-inflated cones (A, B and C)

User experiment

- 49 participants
  - UC1 : 30 part. (mean 37.17 years)
  - UC2 : 19 part. (mean 28.37 years)

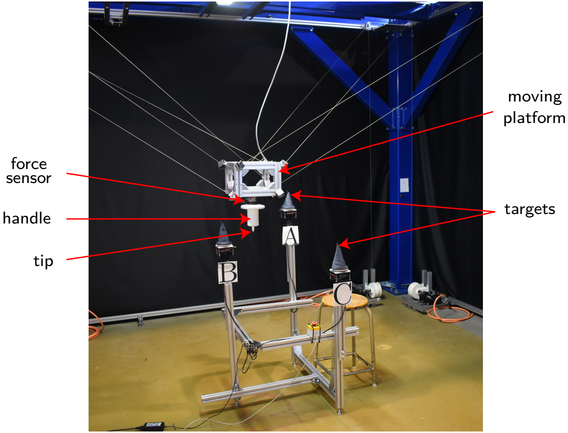


Figure 17: User experiment setup

UC1 & UC2 : a comparative user-experiment

Performance criteria definition

Performance criteria (dependant variables)

- *Time* (Completion time of segments)
- *Deviation* (Mean of the segment deviation)
- *Transparency*

Independant variables

- *PerformedPath*
- *PathType*

Transparency index

$$\mu = \mathbf{v}_n^\mathsf{T} \, \mathbf{f}_{hn} \tag{10}$$

and

$$\nu = 1 - \mu \tag{11}$$

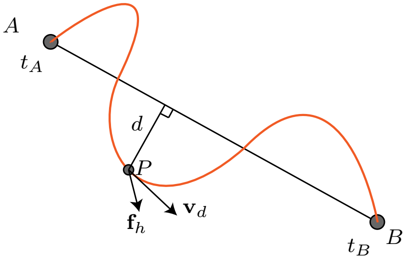


Figure 18: Ideal path (black), end-effector tip path during user experiment (orange)

UC1 & UC2 : a comparative user-experiment

UC1 : Teleoperation with a suspended 3 cables CDPR

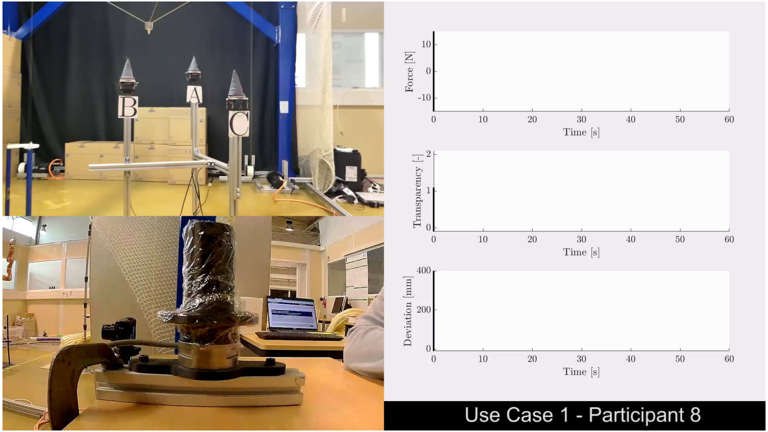


Figure 19: Participant on the UC1 experiment

UC1 & UC2 : a comparative user-experiment

UC2 : Teleoperation with a suspended 3 cables CDPR

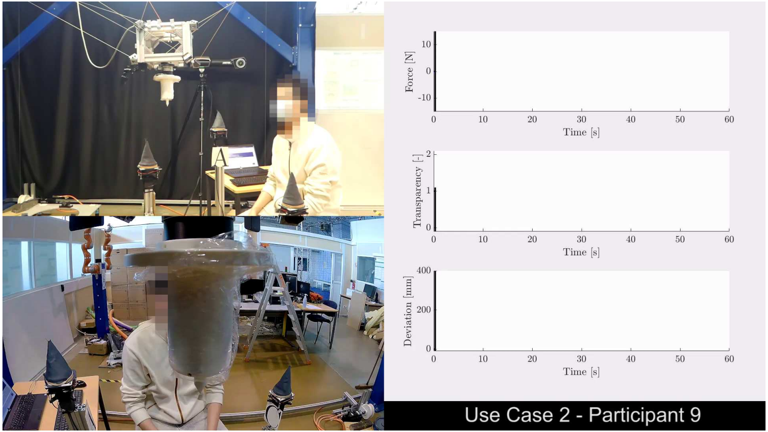


Figure 20: Participant on the UC2 experiment

UC1 & UC2 : a comparative user-experiment

Analysing the performance criteria separately

Table 1: Overall performance of UCs

	Time [s]		Deviation [mm]		Transparency [-]	
	Mean	SD	Mean	SD	Mean	SD
UC1	18.04	5.47	74.48	26.23	0.60	0.08
UC2	8.91	3.19	28.31	11.04	0.77	0.12

Results

- More variability for *Time* and *Deviation* in UC1
- Lower *Time*, *Deviation* and *Transparency* in UC2

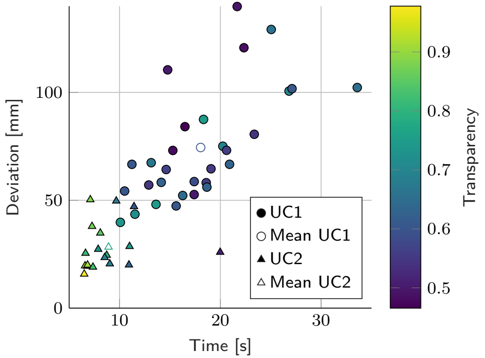


Figure 21: Participant performance comparison UC1/UC2, each circle is a UC1 participant and each triangle is a UC2 participant

UC1 & UC2 : a comparative user-experiment

Comparing the training effect of UCs

Linear regression

$$y = a_0 + a_1 \text{PerformedPath} \tag{12}$$

Table 2: Linear regression coefficients of performance criteria for each UC, ** denotes a p-value inferior to 0.01, * denotes a p-value between 0.01 and 0.05 and n.s. indicates a p-value superior to 0.05

	Time		Deviation		Transparency	
	a_0	a_1	a_0	a_1	a_0	a_1
UC1	21.979	-0.214 **	0.082	-5.086e-04 **	0.602	1.204e-04 n.s.
UC2	10.027	-0.033 **	0.032	-8.746e-05 **	0.715	1.005e-03 **

Results

- Stronger progression in UC1
- Transparency decreasing in UC2

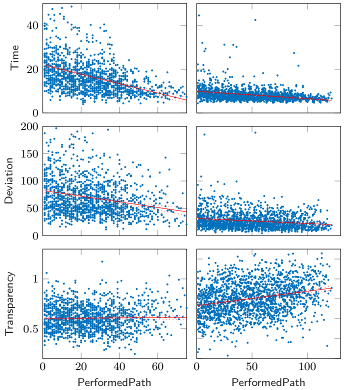


Figure 22: Plot of linear regression of all observations of performance criteria for each UC, blue scatter data are the observed segment and solid red line plot are linear model

Conclusion

Challenges addressed during the thesis

- Elasto-geometric modelling of CDPR
  - Accounting for actuation element geometry
  - Accounting for elastic cable elongation
  - Sensitivity and parametric analysis of models
- Development of collaborative control strategies
  - Sharing of human and robot workspace
  - Co-manipulation of CDPRs
- Performance assessment of pHRI trough user-experiment
  - Performance evolution during interaction
  - Studying the learning effect during interactions
  - Modelling the human behaviour during interactions

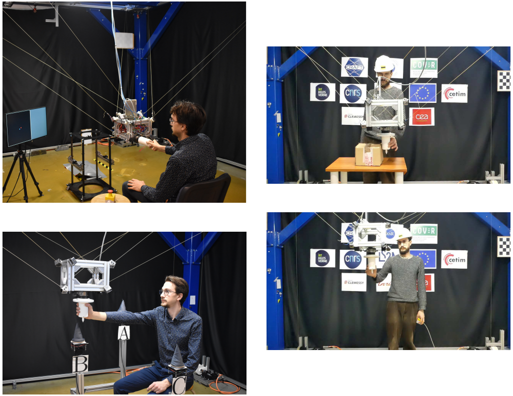


Figure 23: Experiment led during the thesis

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