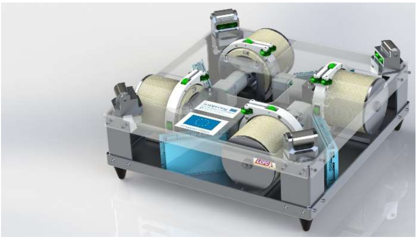
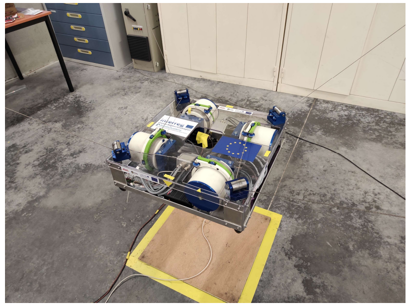
Design and control of cable-driven robot for agile handling of parts in a manufacturing line

Conception et Commande d’un Robot à Câbles pour la manipulation dextre de pièces sur des chaînes de production





By : Atal Anil KUMAR

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LCFC Conception Fabrication Commande

Introduction

- Robotic systems ➔ 4-D tasks (Dirty, Dull, Dumb and Dangerous).
- Robotics ➔ Key driver of competitiveness and flexibility in large scale manufacturing industries.
- Making things easier for manufacturers ➔ Precision machining and assembling to material handling.
- Robots ➔ Simpler to program, integrate and install.
- Collaborative work environments ➔ Future requirement.

Motivation

Rise of health costs and physical risks

7% of the overall productivity loss per year

High costs to the individual companies

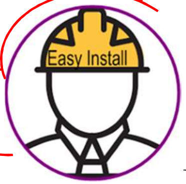
WMSDs

Repetitive work

Handling of heavy parts for a long time

To develop a solution to reduce Work-related Musculoskeletal Disorders (WMSDs) in workers using a Cable-Driven Parallel Robot (CDPR) which allows interaction of the worker and robot in a safe way.

Objectives



Modular

Reconfigurable

Four cables

- Underactuated system !
- Choice of outputs to be controlled

Simple anchors in the environment

Cable-Driven Robot

Motors on the moving platform

User friendly interface

- Interface using C++
- Possibility of integrating with haptic device ?

- Platform is a rigid body with 6 Degrees of Freedom (DoF)
- Consider its inertia

State of art: Cable robots

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- Parallel Wire Robots (PWRs)- also known as Cable Driven Parallel Robots (CDPRs)
- Cable-driven parallel robots - special class of parallel mechanisms in which the end-effector is actuated by cables, instead of rigid-linked actuators.

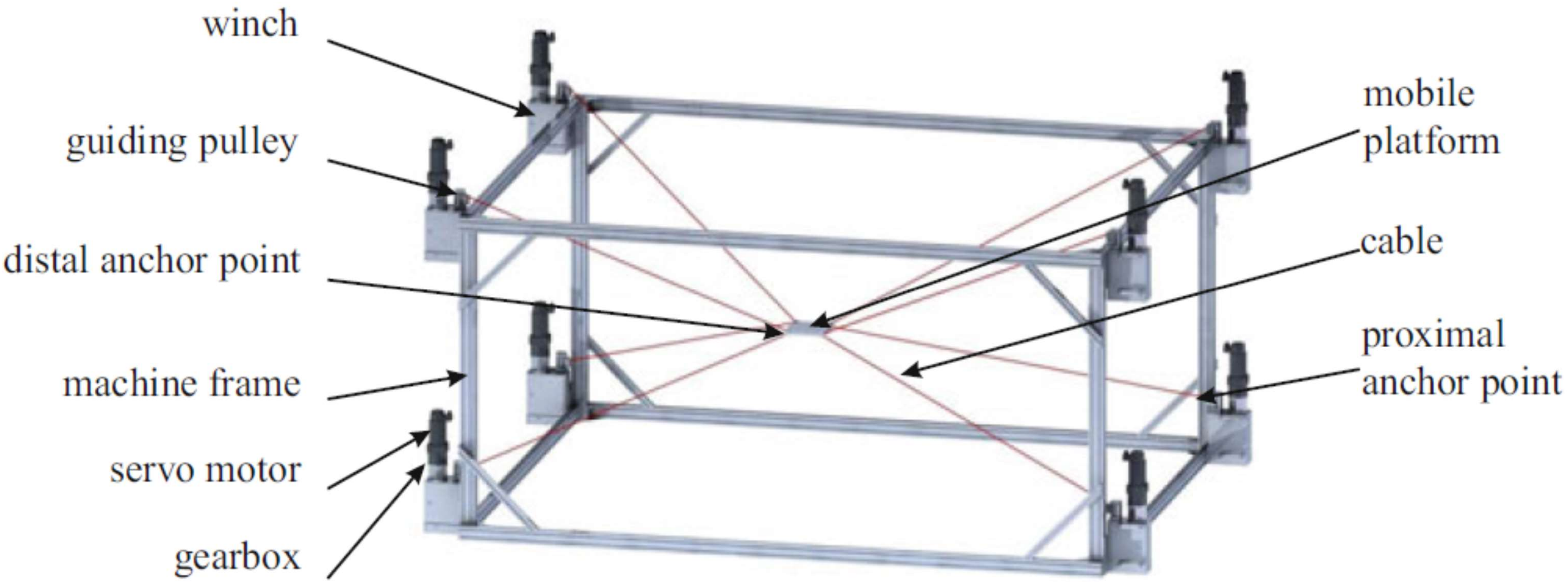

Fig. 1: An example of a CDPR – IPANEMA robot with its various parts

State of art: Advantages and Challenges

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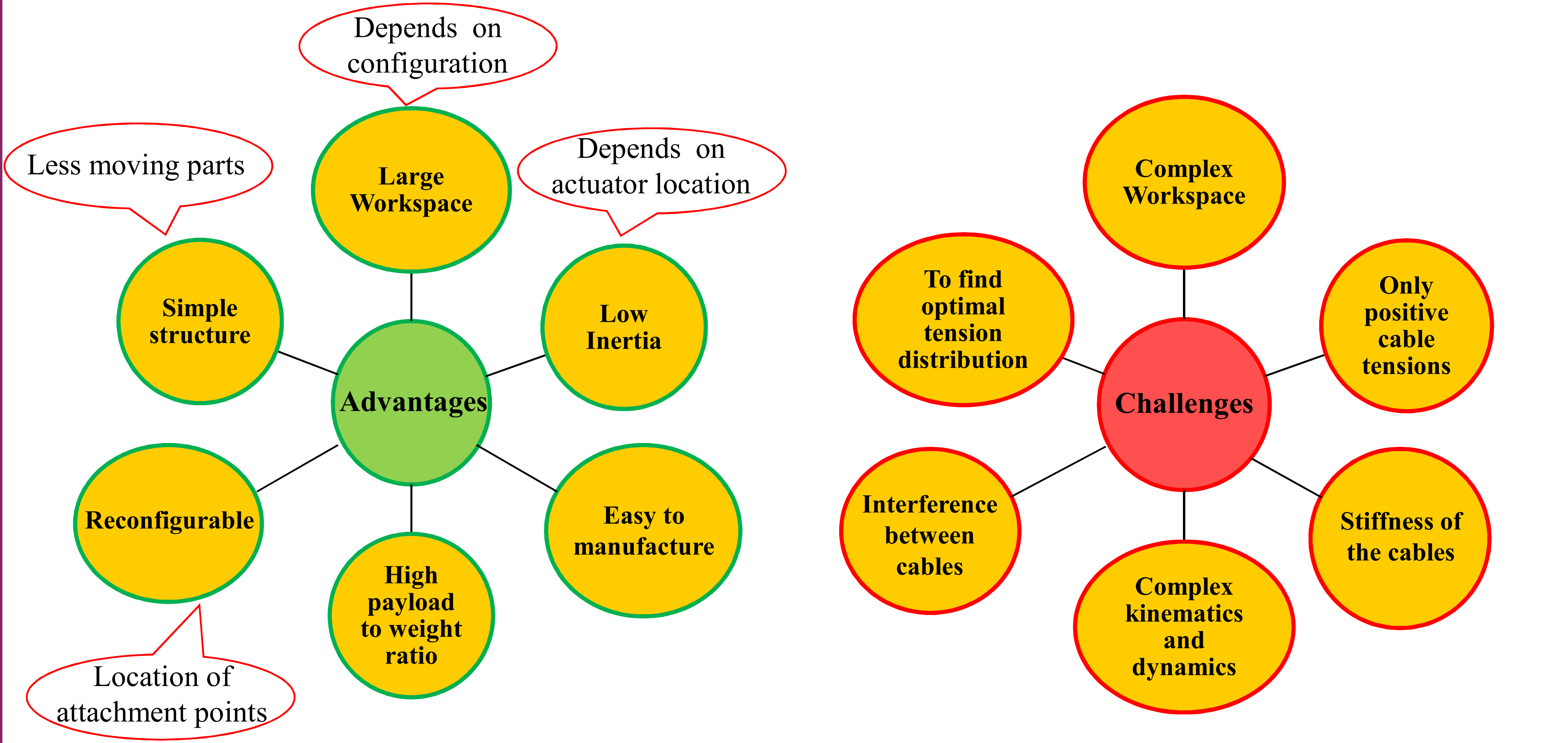

Research gap

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- CDPR with four cables and motors on the moving platform – Not yet implemented for industrial applications.
  - A CDPR with motors on the Moving Platform (MP) and simple anchor points.
  - Benefits ➔ easy to install in a manufacturing line.
  - Inertia of the platform ➔ significant role in the stability of the platform.

- Underactuated system - exciting control challenges
  - Internal Dynamics ➔ MP oscillations, abnormal value of cable forces.
  - Control law ➔ Maintain the stability of the platform.
  - Feedback linearization – common approach.
  - Implement classical control law ➔ Input-Output Feedback Linearization.

CDPR: Dynamic model

Assumption 1: Cable mass is negligible
Assumption 2: Cable is assumed to be taut between points

$$M(X)\ddot{X} + C(X,\dot{X})\dot{X} + G(X) = -J^T\tau \quad (1)$$

$$\begin{bmatrix} mI_{3\times3} & 0_{3\times3} \\ 0_{3\times3} & I_P \end{bmatrix}\begin{bmatrix} \ddot{p} \\ \dot{\omega} \end{bmatrix} + \begin{bmatrix} 0_{3\times1} \\ \omega \times I_P\omega \end{bmatrix} + \begin{bmatrix} -mg \\ 0_{3\times1} \end{bmatrix} = -J^T\tau \quad (2)$$

$p = [p_x, p_y, p_z]^T$, the position vector

$\omega = [\omega_x, \omega_y, \omega_z]^T$, the velocity vector of the orientation

$\theta = [\alpha, \beta, \gamma]^T$, vector of a set of Euler angles

m = mass of the end-effector

I_P = the inertia tensor of the end-effector about point P in the base frame

g = the gravity acceleration vector

$N(X,\dot{X}) = C(X,\dot{X})\dot{X} + G(X)$

Used for control

$$\boxed{M(X)\ddot{X} + N(X,\dot{X}) = -J^T\tau} \quad (3)$$

Moving Platform: Control

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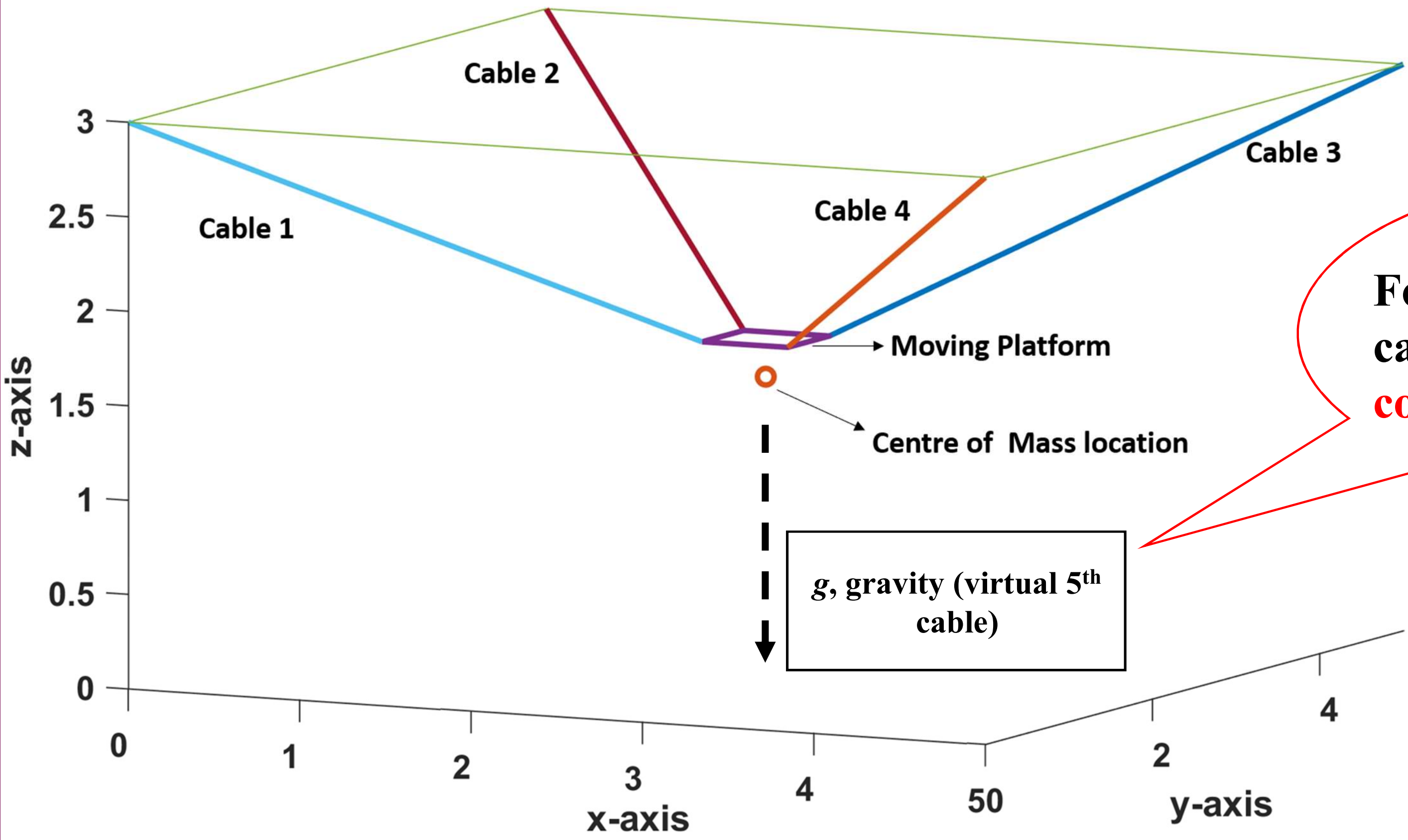

Fig. 2: The CDPR configuration

Four cables + gravity (virtual cable) ➔ 4 DoF can be controlled

Moving Platform: Control

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- Number of Degrees of Freedom (DoF) ➔6

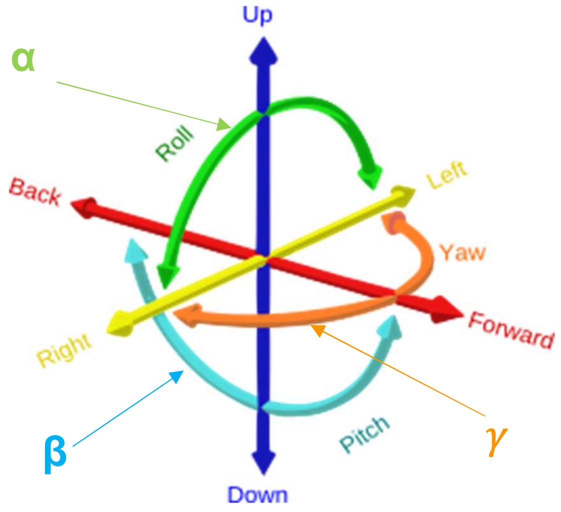

Fig. 3: The six DoFs of a rigid body

Number of actuators ➔ 4

Underactuated by a degree of 2!!

- **DoFs to be controlled ➔ 4: x, y, z and γ (rotation about z-axis)**
- **DoFs that have to be stable for the control to be implemented ➔ 2**
  - **α (rotation about x-axis)**
  - **β (rotation about y-axis)**

Experiments: Test preparation

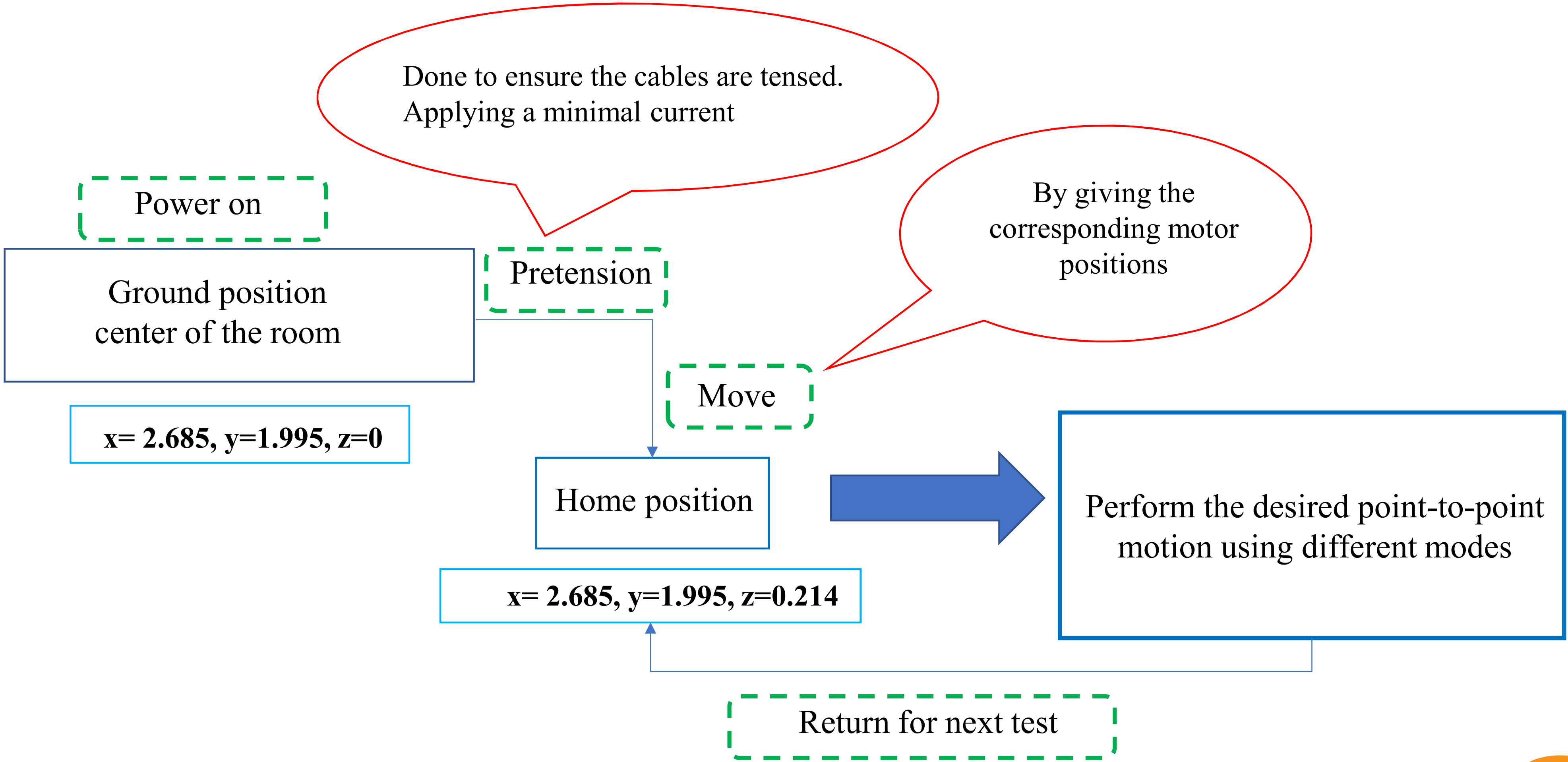

Fig. 4: Test setup for performing the experiments

Experiments: Test preparation

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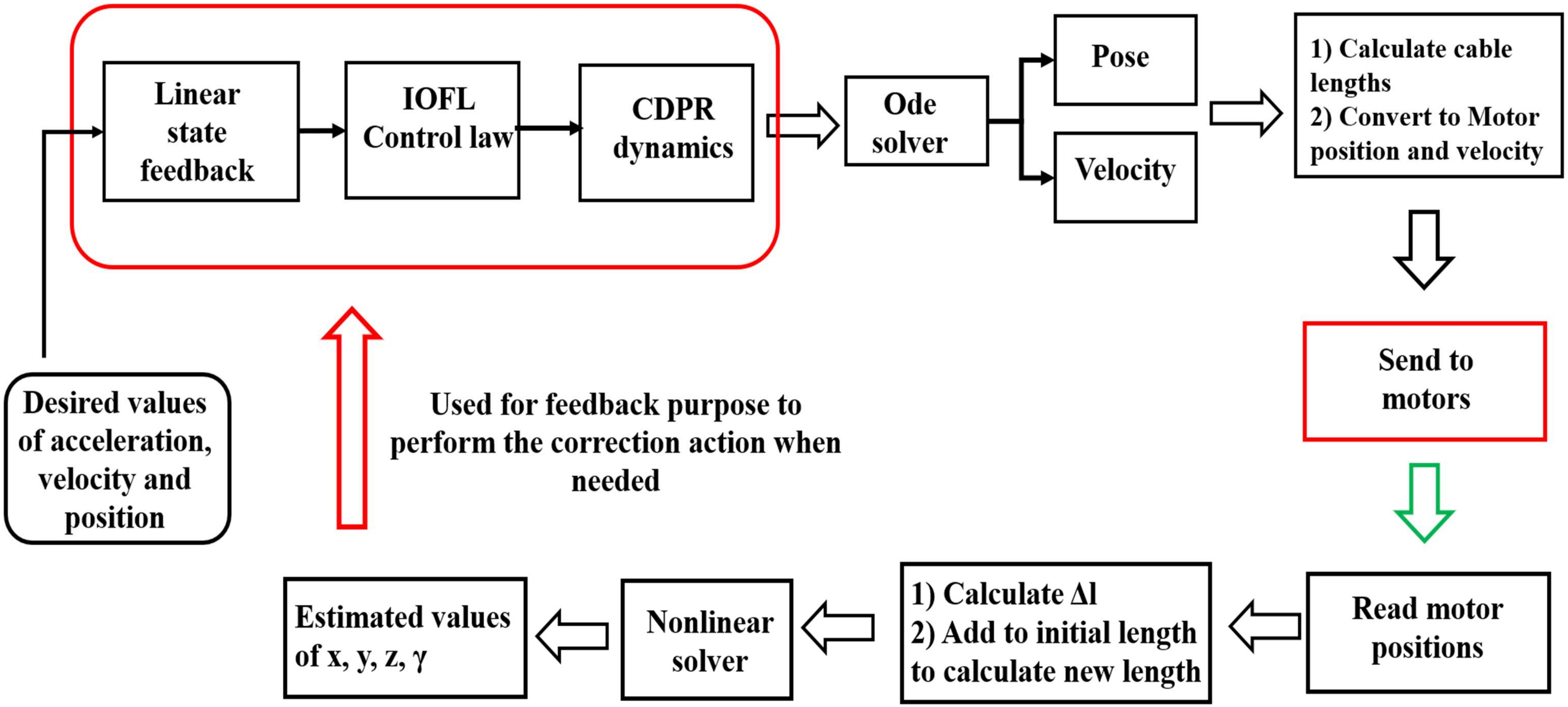

Fig. 5: Block diagram for implementation of control to perform the experiments

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Experimental validation: Test setup

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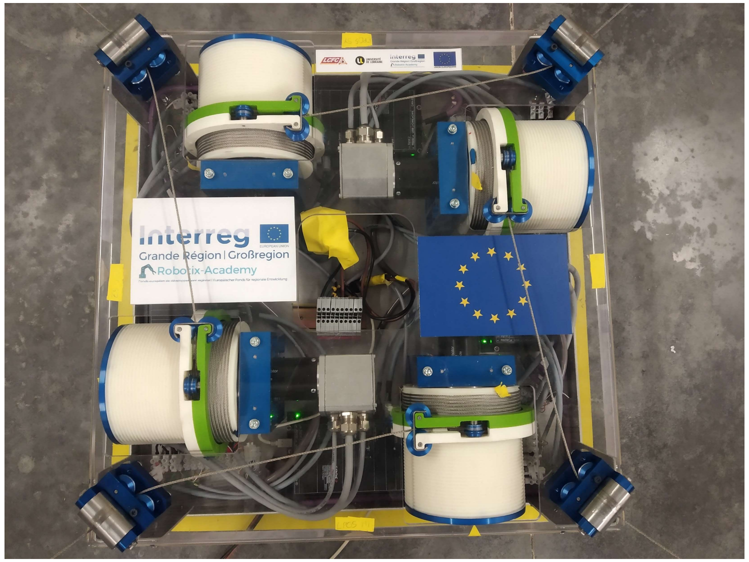

Fig. 6: CDPR prototype

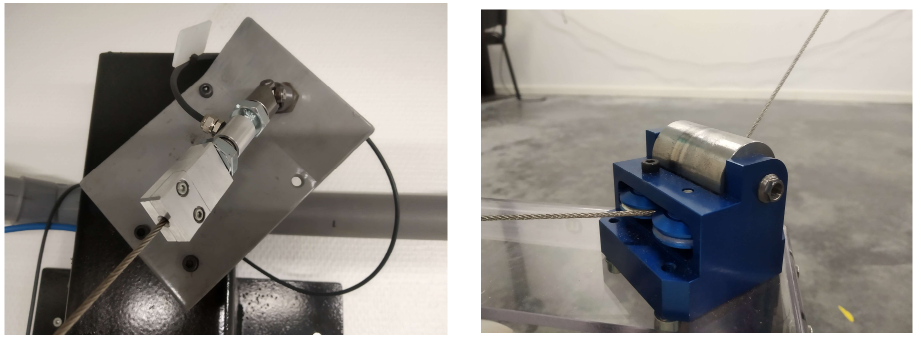

Fig. 7: Simple attachment points fixed in room (left) and arrangement for cable guiding in MP (right)

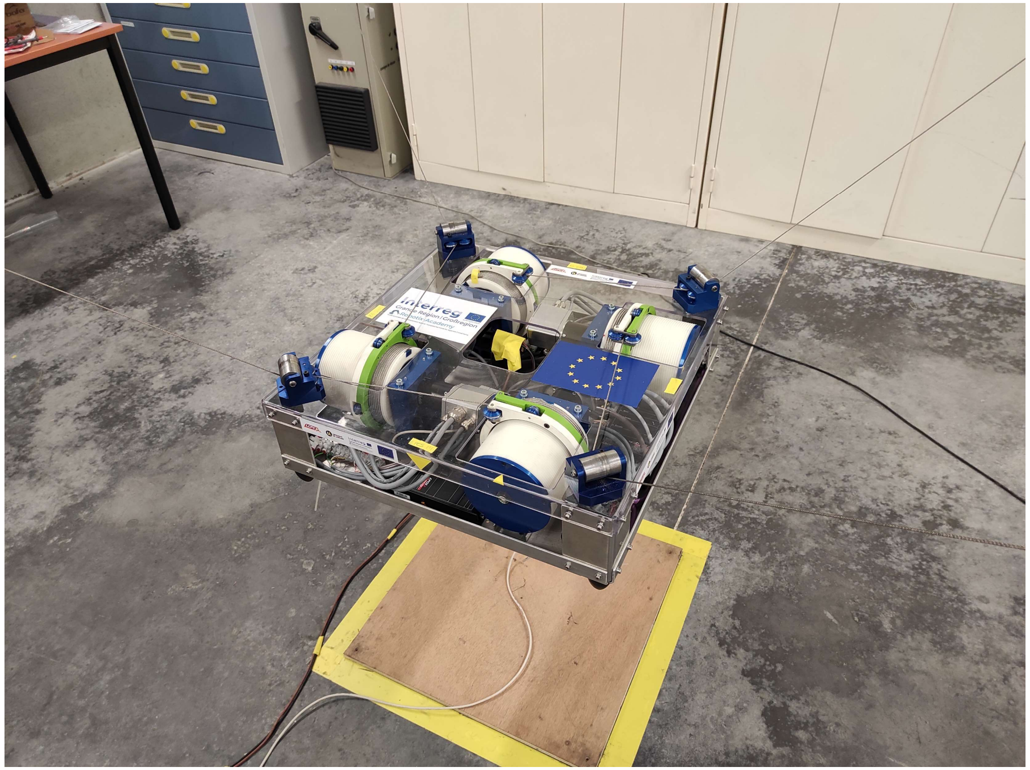

Fig. 8: CDPR in the working environment

Experimental validation: Test setup

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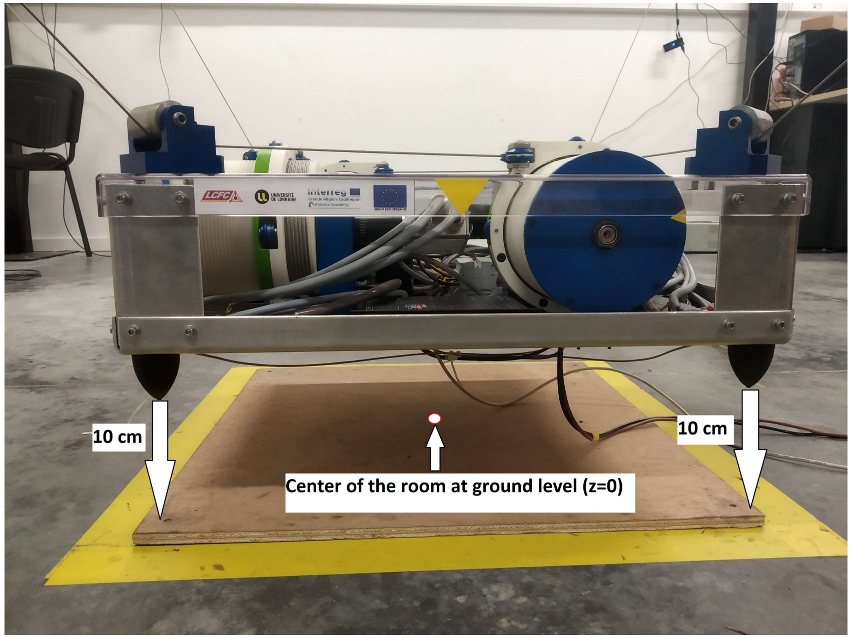

Fig.9: CDPR in home position

Table 1: Parameters for testing

Room dimension (m)	5.37 * 3.99 * 2.97
Platform dimension (m)	0.45 * 0.45 * 0.2
Mass (kg)	23.4 approx.
Inertia (kgm^2)	Ixx = 0.631 Iyy =0.631 Izz = 1.036

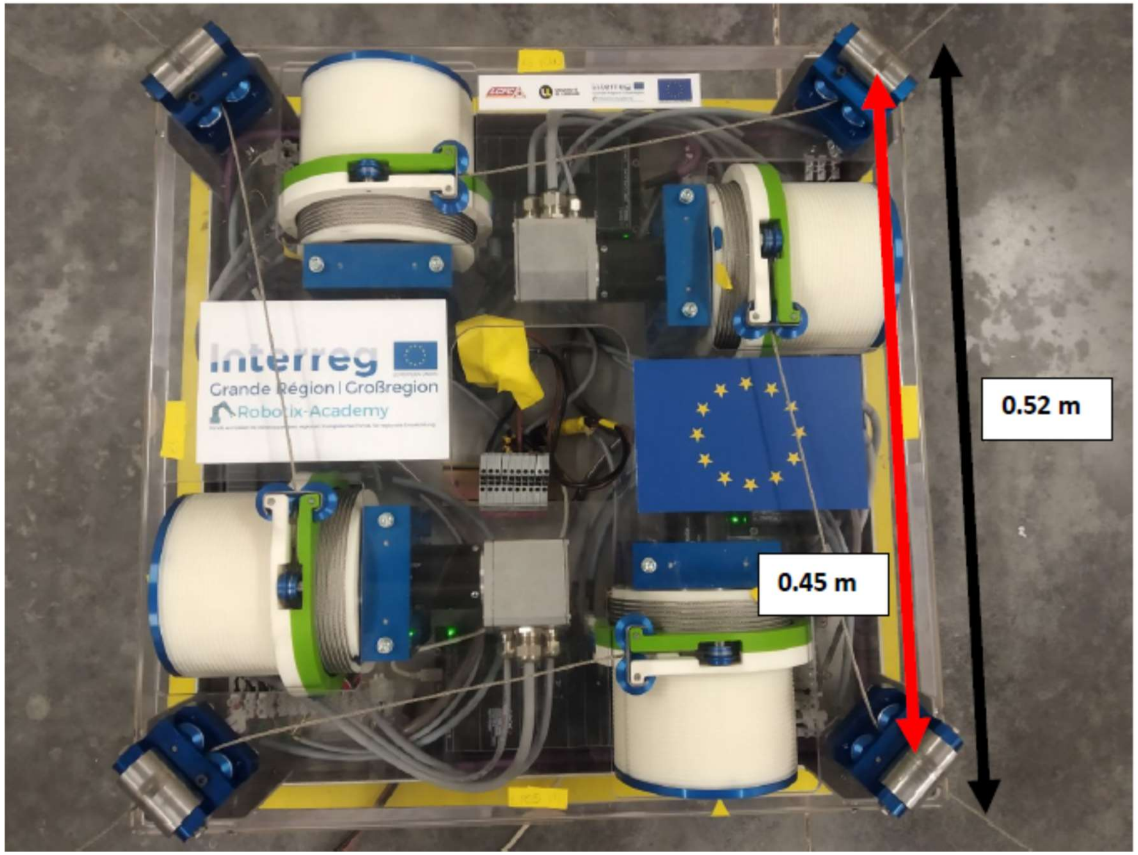

Fig. 10: CDPR top view

Cable exit to exit points are different than the MP dimension

Experimental validation: Test cases (WP5)

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Feedback can be done using motor position, velocity. No need for additional sensors

- Three different velocities for the MP:
  - 0.05 m/s
  - 0.1 m/s
  - 0.2 m/s
- Translation along z-axis:
  - Upward motion, 0.5 m (↑)
  - Upward motion, 1 m [0.5 m (↑) + 0.5 m (↑)]
  - Up-Down motion, 0.5 m (↑) + 0.5 m (↓)

For translation along z-axis, at the center of the room:

$\alpha = 0^o$

$\beta = 0^o$

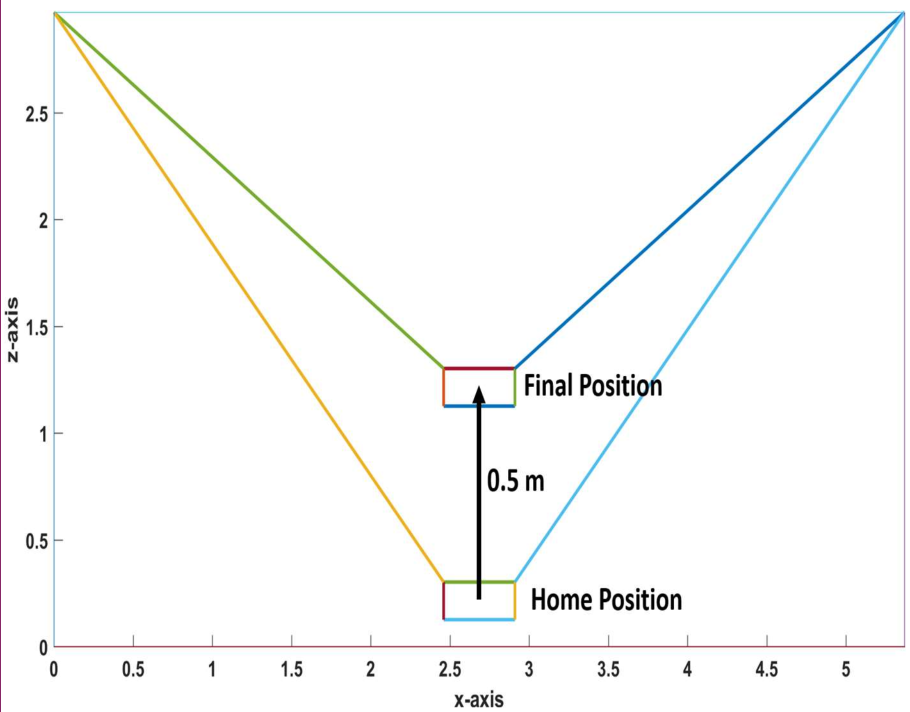
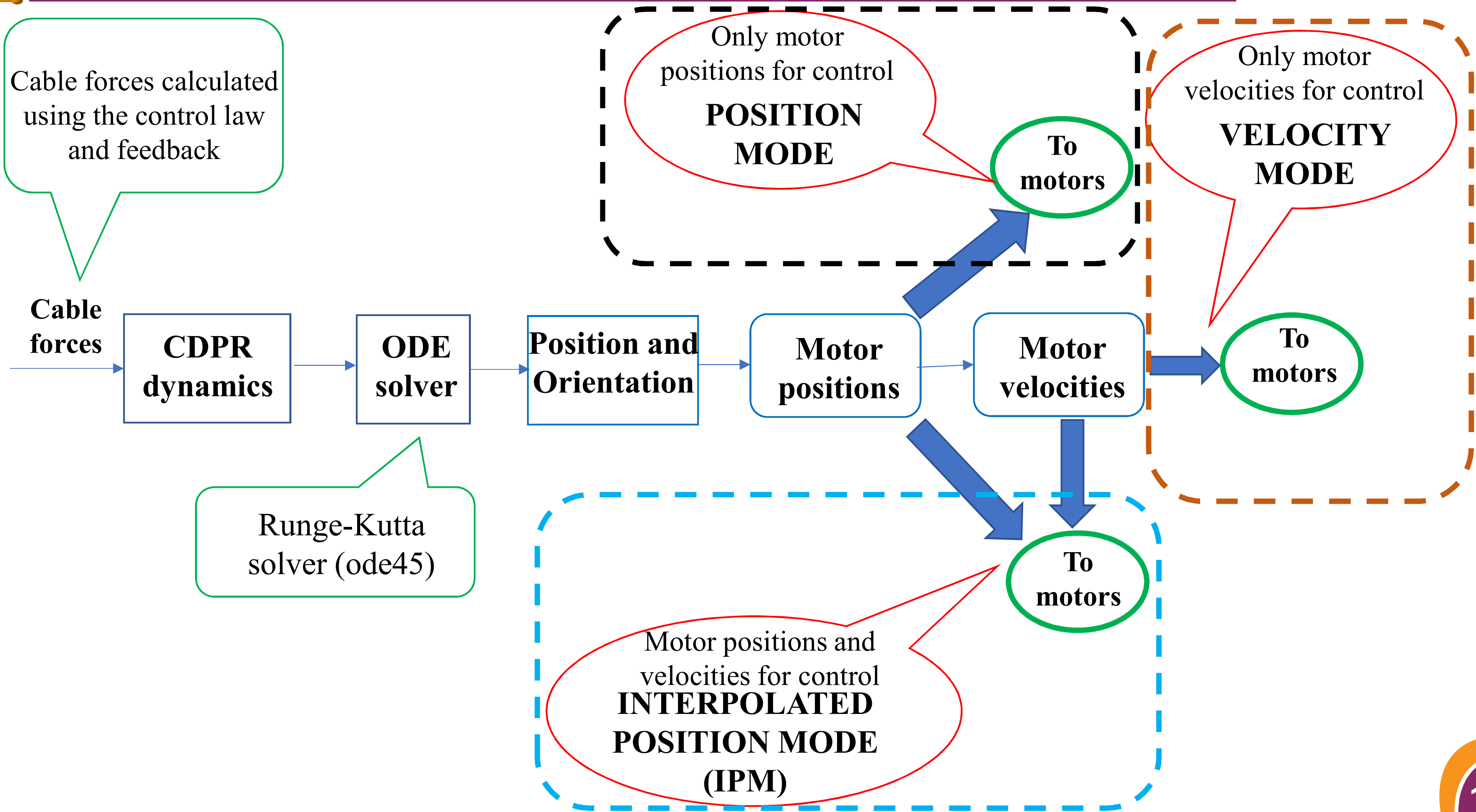


Fig. 11: Upward motion (0.5 m)

Experimental validation: Test modes



Position mode @ v_{des} = 0.05 m/s

k_d= 7.5, k_p= 1

Platform is able to reach desired height in desired time and maintain its position

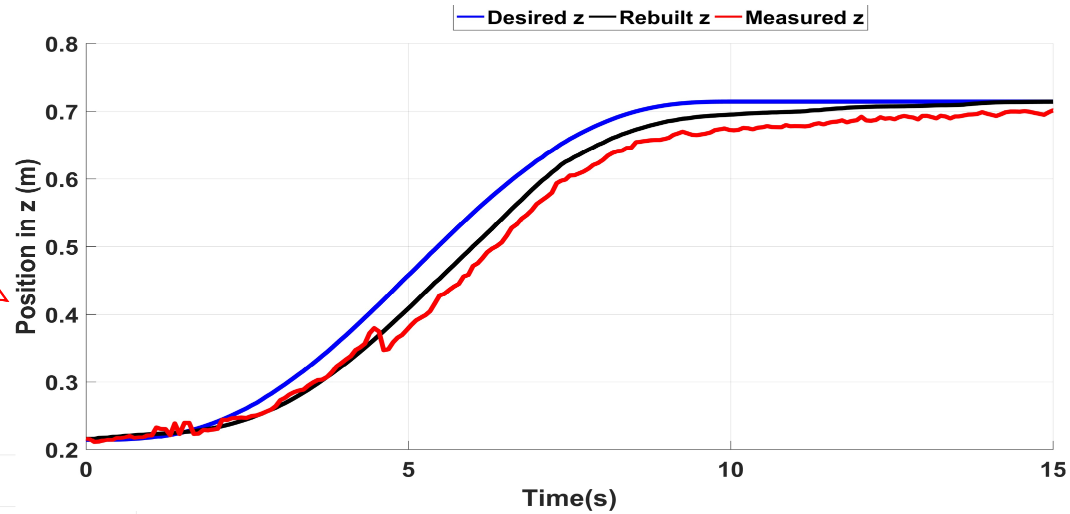


Fig. 12: Comparison between desired, rebuilt and measured platform position in z

Final z_{des} = 0.714 m,
Final rebuilt z =0.71398 m
Final measured z= 0.700 m

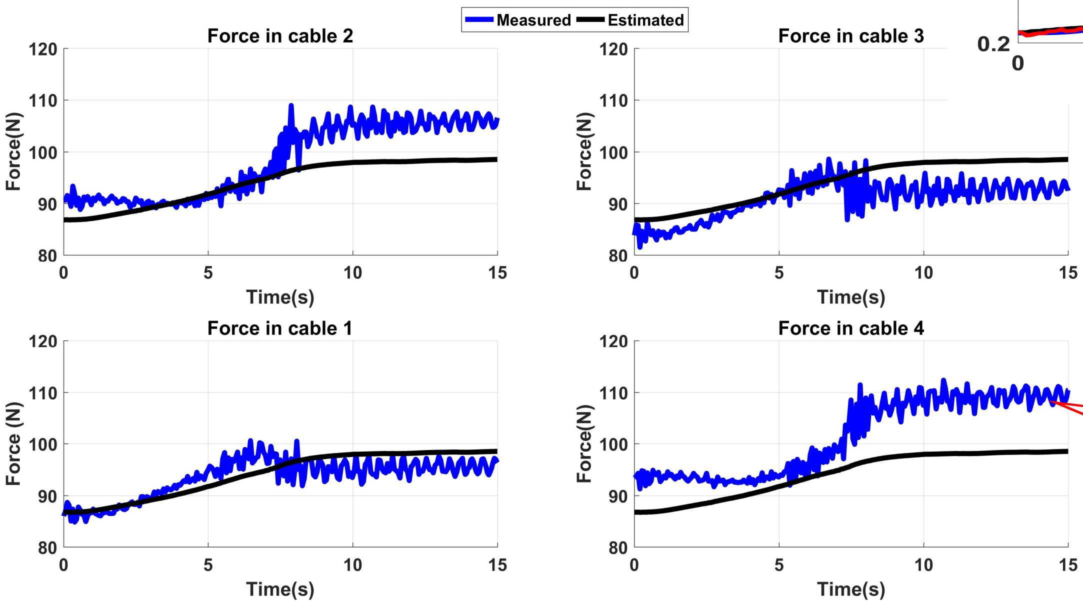


Fig. 13: Comparison between estimated and measured cable forces for the test

Oscillations are seen in cable forces during the motion, but, measured forces are closer to the estimated forces

Velocity mode @ v_{des} = 0.1 m/s

k_d= 5, k_p= 1

Total time for test is 10 s where, 5 s for the point-to-point motion and 5 s rest time

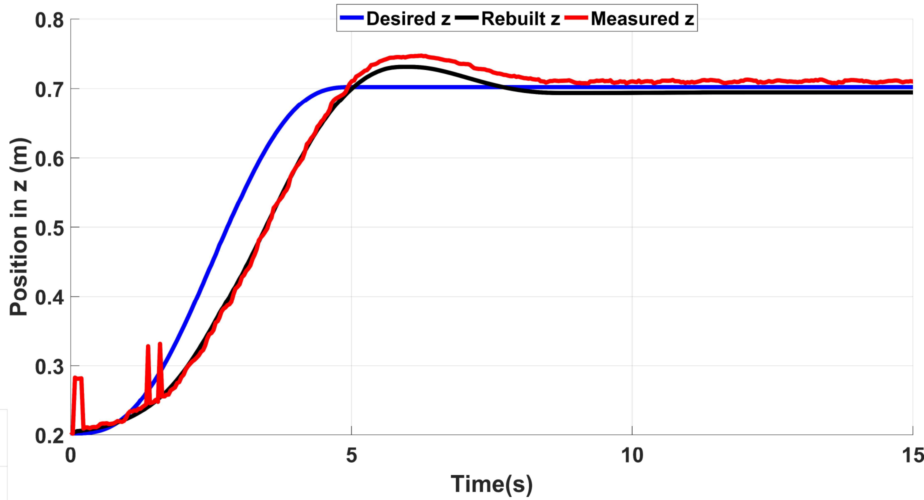


Fig. 14: Comparison between desired, rebuilt and measured platform position in z

Final z_{des} = 0.714 m,
Final rebuilt z =0.6998 m
Final measured z= 0.7204 m

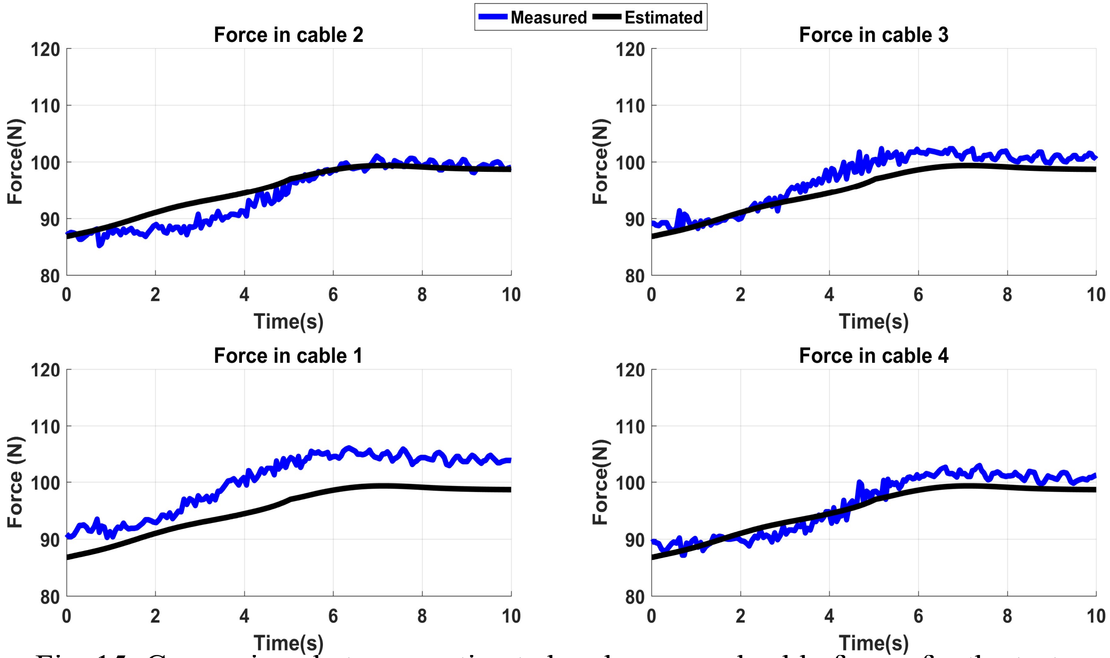


Fig. 15: Comparison between estimated and measured cable forces for the test

Velocity mode ➔ amplitude of oscillations are reduced.

IPM mode @ $v_{des} = 0.2$ m/s

$k_d = 4.95$, $k_p = 1$

Slower response time

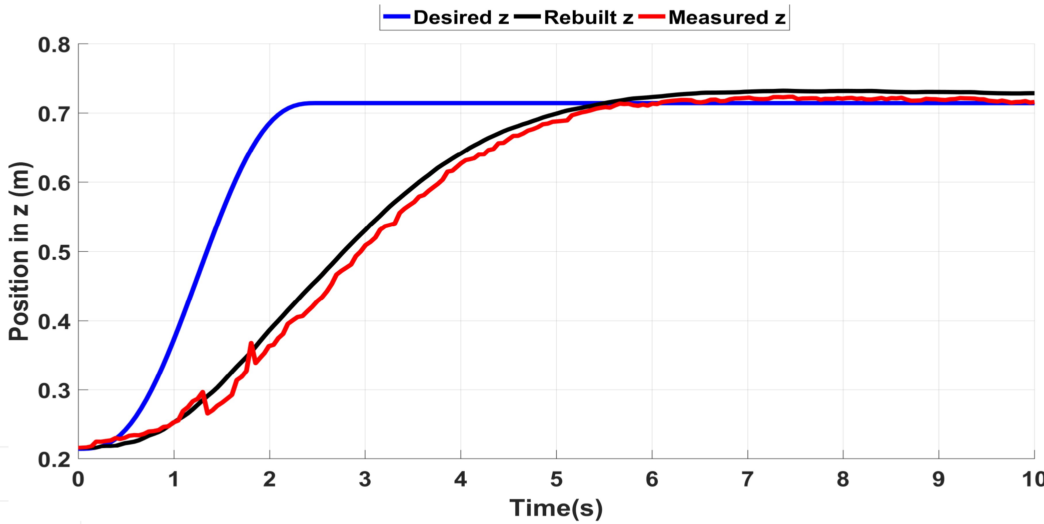


Fig. 16: Comparison between desired, rebuilt and measured platform position in z

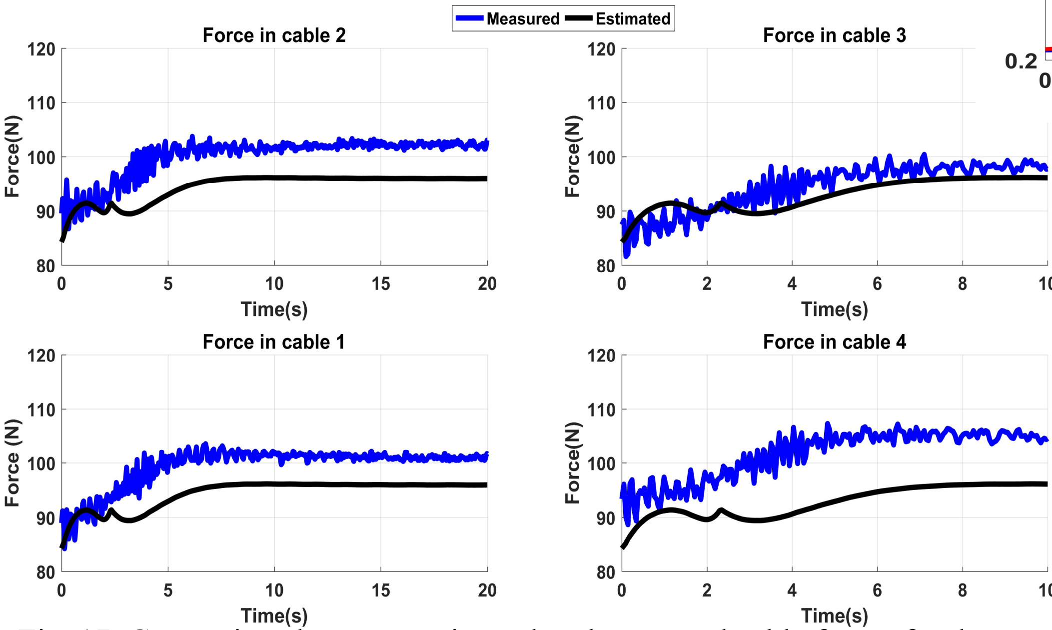


Fig. 17: Comparison between estimated and measured cable forces for the test

Final $z_{des} = 0.714$ m,
Final rebuilt z =0.716035 m
Final measured z= 0.7152 m

All the three modes successfully validate the control law for the desired point-to-point motion

Comparison: Different modes @ v_{des} = 0.05 m/s

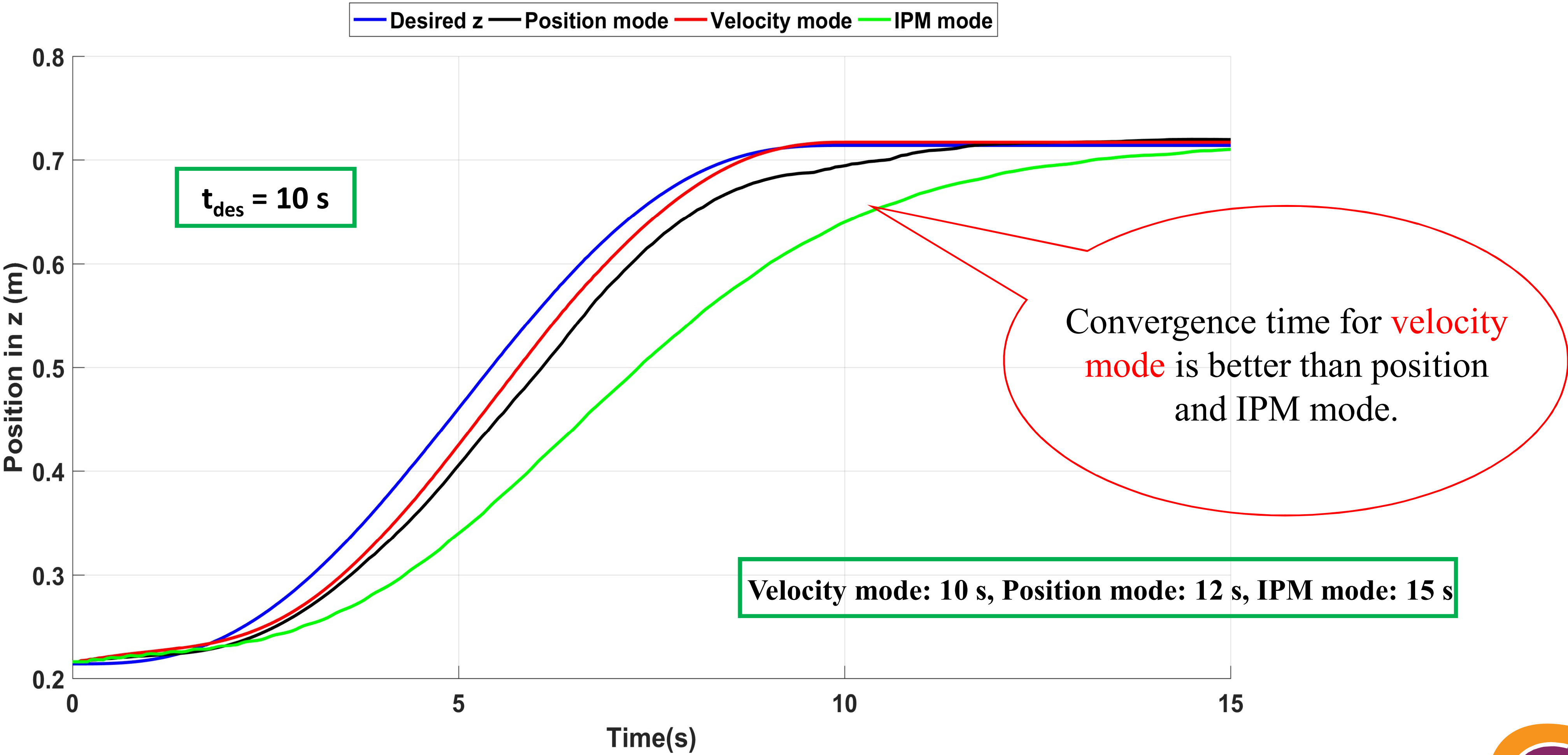


Fig. 18: Comparison between desired z, and rebuilt z using different modes for $\mathbf{v_{des}}$ = 0.05m/s

Experimental validation: Results of other motions

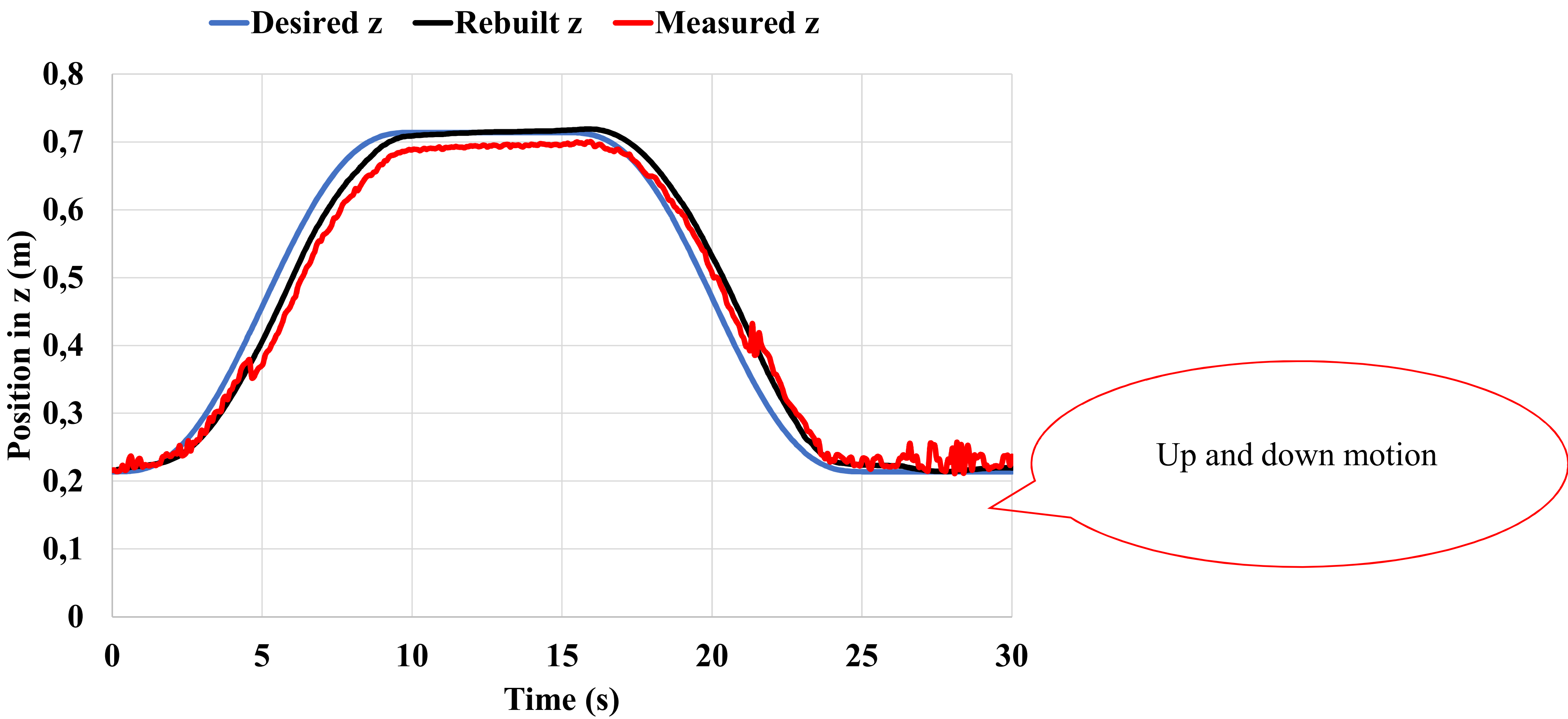


Fig. 20: Comparison between desired, rebuilt and measured platform position in z to go up and down

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Observations:

- MP ➔ able to achieve the desired motion with acceptable error.
- Three values of the desired velocities (0.05 m/s, 0.1 m/s, 0.2 m/s) ➔ three different profiles for the cable forces, but are able to satisfy the necessary behavior for the MP.
- The starting values of cable forces ➔ Not always the same for each tests.
  - Due to pretension, coiling of the cable in the winch
  - Position errors due to measurement
- High oscillations in each cable during the start of the trajectory.
  - Due to the oscillations already present in the cables when they reach the home position

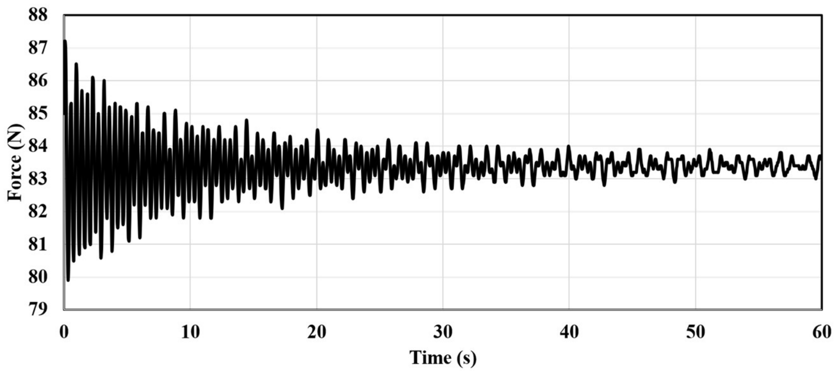

Fig. 21: Cable force after reaching home position from ground

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Thank you!