Application of Motion-Cueing Algorithm on a Cable-Driven parallel robot

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In collaboration with:
Fraunhofer-Institut für Produktionstechnik und Automatisierung IPA

Under the supervision of:
Prof. Dr. rer. nat. Felix Hüning
Chrisitan Michael Lehnertz, M.Sc

Aadithya Ramamurthy (3304090)
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IPA

CONTENTS

INTRODUCTION

- Motion simulators replicate real-world motion.
- Mainly used in aviation and automotive industry.
- Direct integration → Platform limit violations.
- Motion cues → Intertial forces perceived by humans.
- Motion Cueing Algorithms (MCAs) simulate these cues.
- Hexapods (Stewart-Gough platform) → Traditionally used.

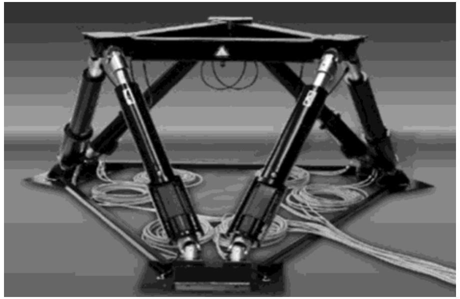

Fig 1: A typical hexapod platform [1]

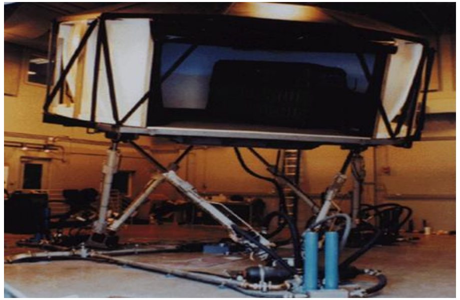

Fig 2: IOWA driving simulator [2]

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MOTIVATION AND OBJECTIVE

- Hexapods → limited motion range.
- Cable-Driven Parallel Robots (CDPRs) offer:
    - Larger motion range
    - High-speed maneuvering capacity
    - Long duration manoeuvres
    - Higher payload-to-weight ratio
- Implementing MCA on CDPR IPAnema 3.
- Optimising MCA parameters.

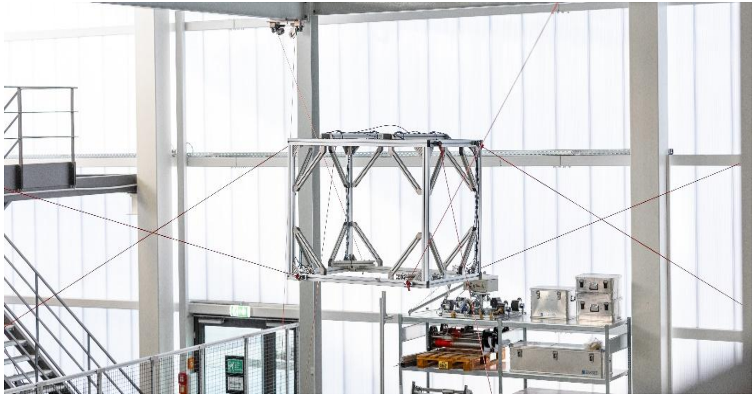


Fig 3: IPAnema 3 at Fraunhofer IPA [3]

FUNDAMENTALS AND LITERATURE

FUNDAMENTALS
Classical Washout Algorithm (CWA)

- Most widely used MCA.
- CWA generates 6-DOF platform commands.
- Channels:
    - Translational
    - Rotational
    - Tilt-coordination
- Four basic ideas are used in a CWA:
    - Input Scaling
    - High-Pass (HP) Filtering
    - Low-Pass (LP) Filtering
    - Washout

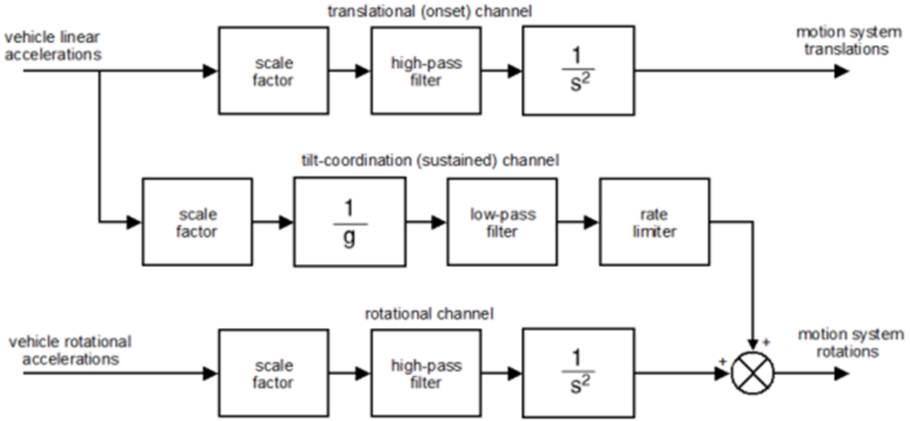


Fig 4: General Block diagram of CWA [4]

FUNDAMENTALS
Cable-Driven Parallel Robots

- Main components:
  - Fixed platform
  - Mobile platform
  - Cables
- Tensioned cables → Controls suspended mobile platform.
- Platform motion → Adjusting cable lengths via winches

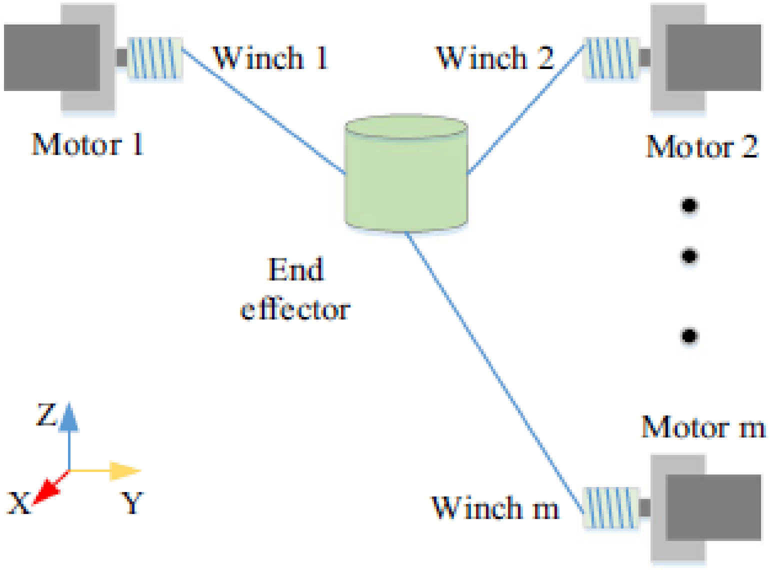


Fig 5: Schematic representation of a CDPR[5]

LITERATURE REVIEW
Key takeaways

- No universally accepted MCA exists.
- CWA is widely used.
- Platform geometry and workspace constraints → MCAs (relevant to CDPRs).
- Parameter optimisation in CWA → Prerecorded simulated trajectory.
- Other algorithms → Real-time adaptation
- Cable-Robot Simulator (CRS) at Max-Planck Institute (MPI): Only CDPR Simulator

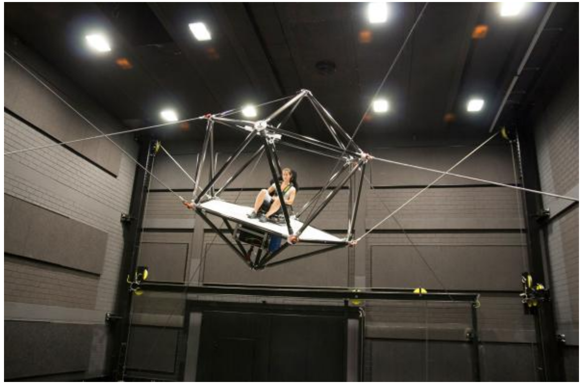


Fig 6: CRS at MPI[6]

LITERATURE REVIEW
Research questions

- How…
    - CWA on a CDPR?
    - Integration of workspace and geometry constraints of IPAnema 3 with CWA?
    - Optimisation to tune parameters of CWA?
    - Different trajectory types and payload affect the CWA parameters?

METHODOLOGY AND IMPLEMENTATION

METHODOLOGY AND IMPLEMENTATION
Setting up CWA

- CWA: First implemented with manually tuned parameters.
- Motion data → FlightGear.
- CWA processes inputs → Generates 6-DOF pose trajectories.
- Force feasibility → Computing cable forces .
- Iterative modification of parameters.

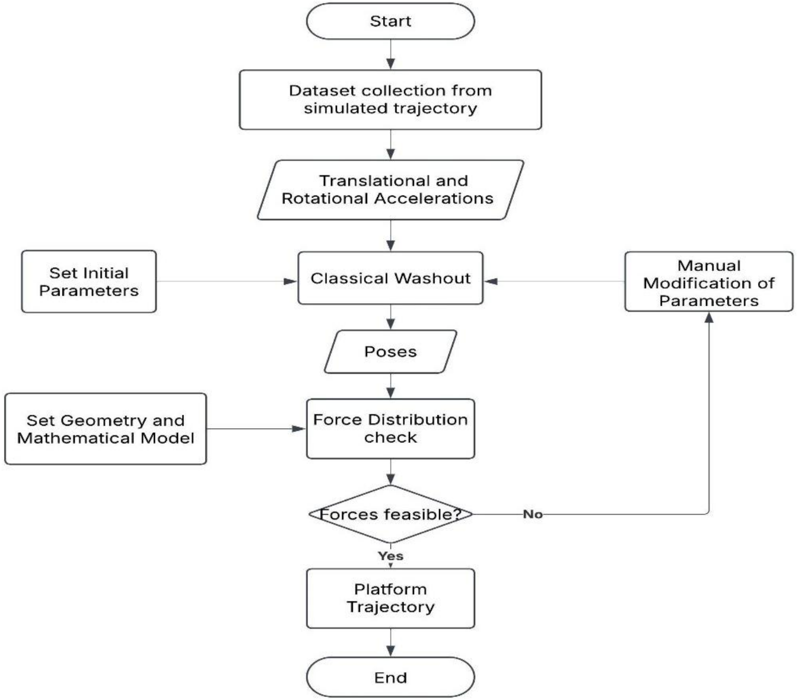


Fig 7: Flowchart of manually tuned CWA

METHODOLOGY AND IMPLEMENTATION
Setting up CWA

- Implemented in Python.
- Input → CSV dataset.
- Based on the Reid-Nahon (UTIAS)[7] implementation.
- Butterworth filters → Minimal distortion.
- Output → Pose commands for the IPAnema 3 platform.

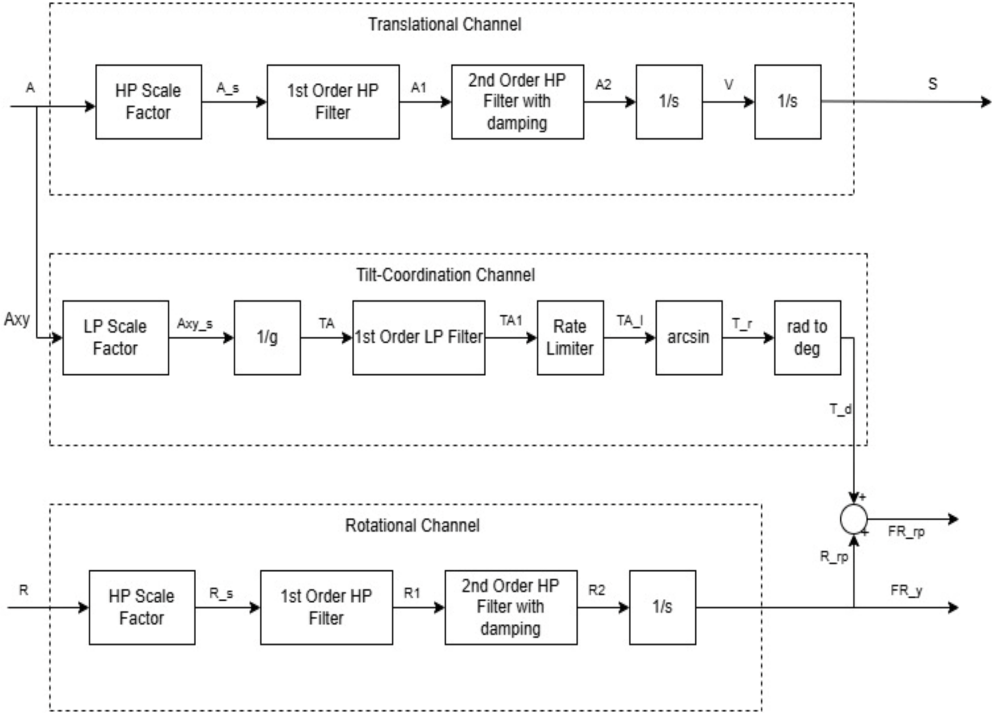


Fig 8: CWA implementation block diagram

METHODOLOGY AND IMPLEMENTATION
Setting up CWA – Translational Channel

- Input: Translational acceleration.
- Scaling factor (0–1): Prevents excessive force outputs.
- Filtering Stages:
  - First-order HP filter: Removes sharp and sustained translational accelerations.
  - Second-order HP filter: Adjustable damping for translational washout.
- Double integration → Translational pose.

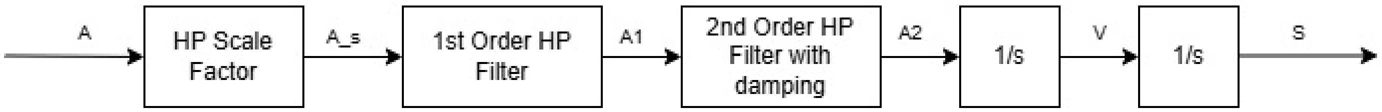
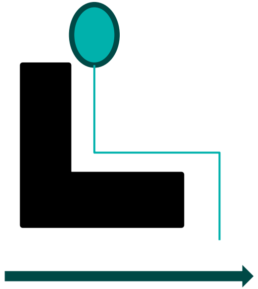


Figure 9: Translational Channel Implementation block diagram



METHODOLOGY AND IMPLEMENTATION
Setting up CWA – Rotational Channel

- Input: Rotational rate.
- Scaling factor (0–1): Reduces rotational intensity.
- Filtering Stages:
    - First-order HP filter: Removes sharp and sustained rotational rates.
    - Second-order HP filter: Adjustable damping for rotational washout.
- Single integration to compute angular displacements → Rotational pose.

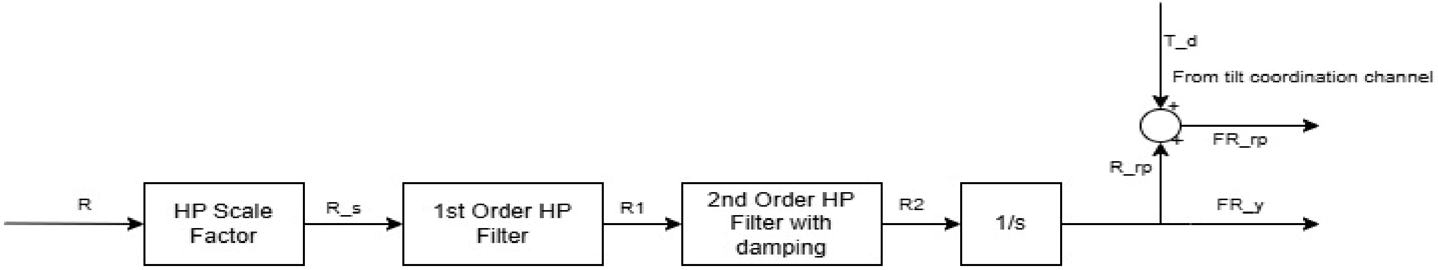
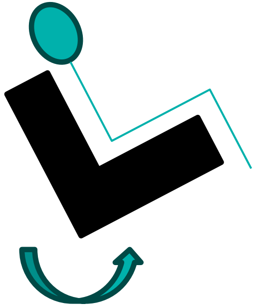


Figure 10: Rotational Channel Implementation block diagram



METHODOLOGY AND IMPLEMENTATION
Setting up CWA – Tilt-Coordination channel

- Simulates low-frequency (LF) translational accelerations using gravity-induced tilt.
- Input: Translational acceleration data (only X and Y axes).
- Scaling factor (0–1).
- Division by ‘g’.
- First-order Low-Pass (LP) filter: Same as HP Cut off from translational channel.
- Rate limiter (0.00524 rad/s² or 3°/s)
- Arcsine function → Tilt angles (roll/pitch).
- Radians to Degrees → Rotational channel.

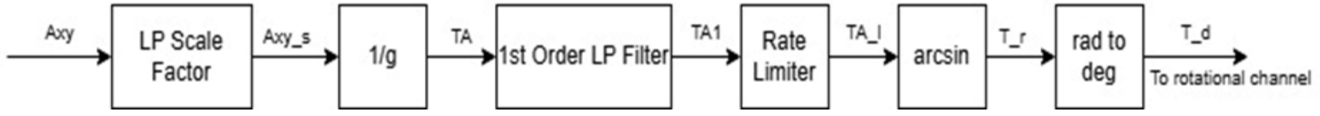
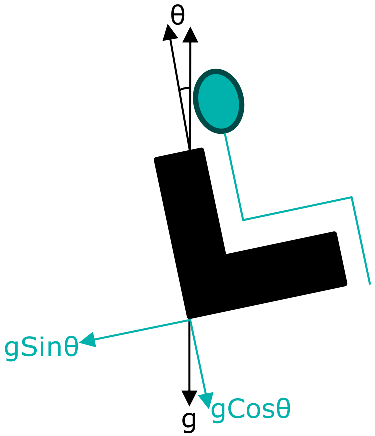


Figure 11: Tilt-Coordination Channel Implementation block diagram



METHODOLOGY AND IMPLEMENTATION
Force Feasibility with CWA

- WiPy: Python wrapper for WireLib
  - CDPR geometry & kinematics.
  - Workspace calculation using cable force distribution.
- IPAnema 3:
  - 8 cables
  - 6 DOF
  - Force Limits: 100 N – 3000 N
- CWA pose → checked for force feasibility.
  - Feasible → cable forces returned
  - Infeasible → marked invalid
- Results → CSV

METHODOLOGY AND IMPLEMENTATION

Cost function optimisation

- Optimisation → Damping factors (Translational)
- Cost function → Manually tuned CWA.
- Set parameter bounds.
- Calculate cost.
- Iterative process:
  - Check force feasibility.
  - Not feasible → retain previous parameters.
  - Feasible → proceed to optimisation step.
- Cost optimisation
  - Cost minimised → Stop.
  - Not minimised → Update parameters and repeat process.

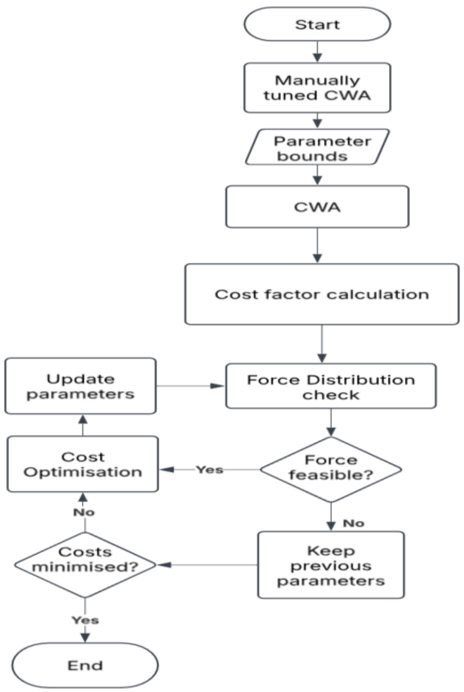


Fig 12: Flowchart of Cost function optimisation

METHODOLOGY AND IMPLEMENTATION
Defining the Cost function

- Force factor(Cost) → Absolute difference between the original and processed forces post CWA, normalized by the original force magnitude.
- Normalisation → Relative Absolute Error method by adding a small offset, given by:

$$Force\ Factor\ (Cost) = \frac{|\ F_{axis\_post} - F_{axis}\ |}{|\ F_{axis}\ | + Offset}$$

- The offset is added for two reasons:
    - Avoiding division by zero.
    - Mitigating outliers in small forces.
- Cost of trajectory → mean of force factor across all datapoints.

METHODOLOGY AND IMPLEMENTATION
Optimisation of Washout Damping Parameters

- Implemented using scipy.optimize.minimize() with L-BFGS-B method.
- Force Distribution Validation and Cost Evaluation:
  - Applies damping → Generates trajectory.
  - Force feasibility check for each pose.
  - Returns cost if force feasible, or penalty if invalid.
- Minimising the cost:
  - Set Bounds for parameters.
  - If minimize() finds a solution → Optimised damping parameters are assigned to the CWA.
  - If no solution is found → Manually tuned damping parameters are retained.

EVALUATION AND RESULTS

EVALUATION AND RESULTS
Evaluation of customised CWA

- Trajectory: Normal take-off and landing with limited manoeuvres.
- Scaling factors and filter cut-off frequencies → Fixed.
- Z-axis force → -1000 N (~102 kg payload).
- Manual tuning → Ensured force feasibility.

EVALUATION AND RESULTS
Evaluation of customised CWA

Effect of Cutoff Frequencies in Translational channel:

- HP-filtered signals → Short, high-frequency (HF) acceleration bursts.
- LP-filtered signals → Sustained and high magnitude change in accelerations.
- Effective separation confirms correct filtering.

EVALUATION AND RESULTS
Evaluation of customised CWA

Effect of Cutoff Frequencies in Translational channel:

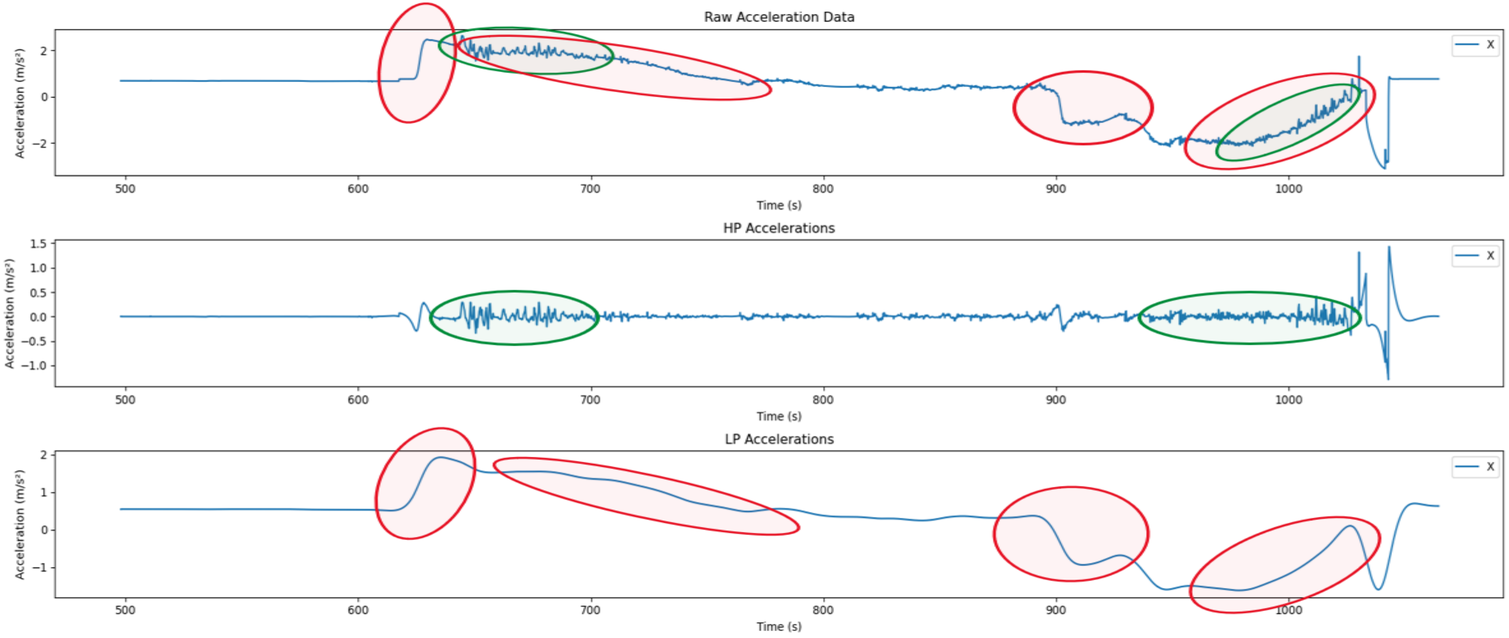


Fig 13: Comparison of input accelerations to filtered accelerations X axis translation

EVALUATION AND RESULTS
Evaluation of customised CWA

Effect of Cutoff Frequencies in Translational channel:

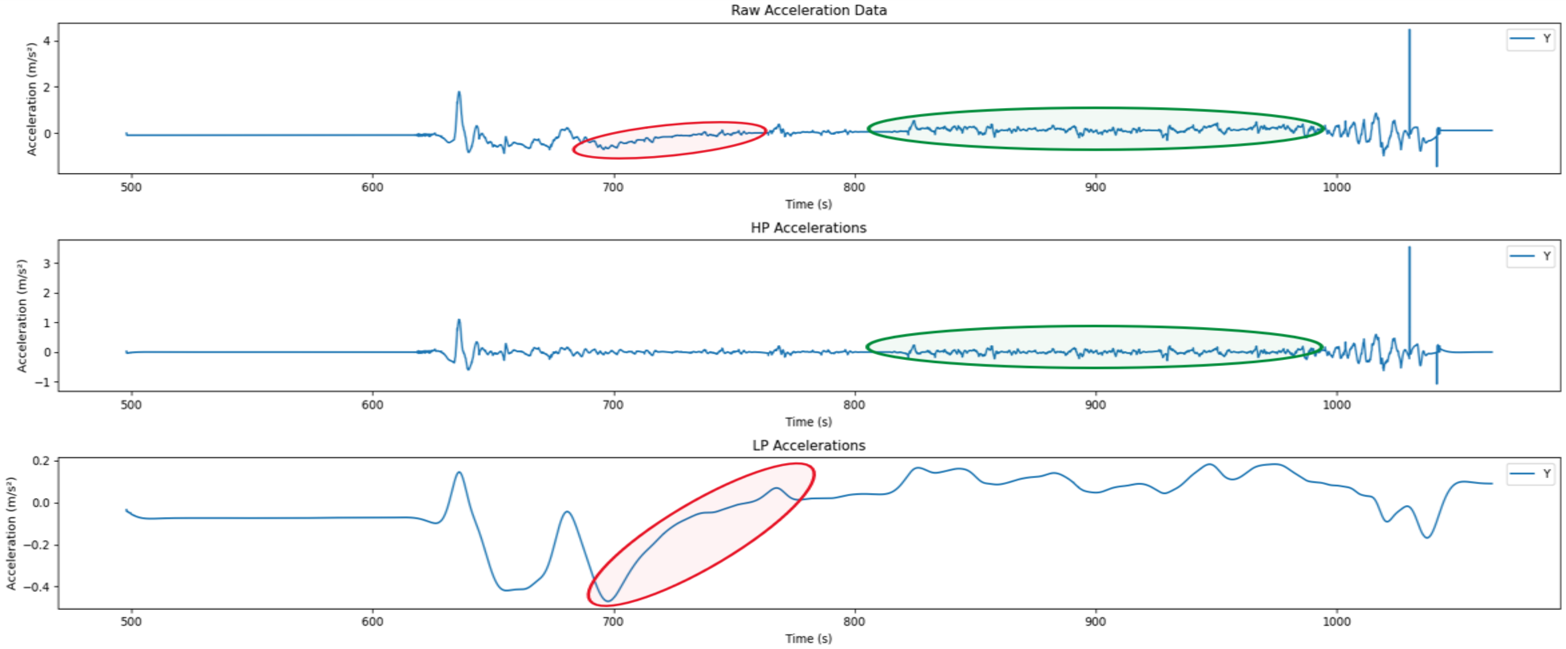


Fig 14: Comparison of input accelerations to filtered accelerations Y axis translation

EVALUATION AND RESULTS
Evaluation of customised CWA

Effect of Cutoff Frequencies in Translational channel:

- Unfiltered integration of raw accelerations → Large position values due LF drift.
- HP filtering reduces this drift.
- Residual drift emphasizes the need for washout damping.

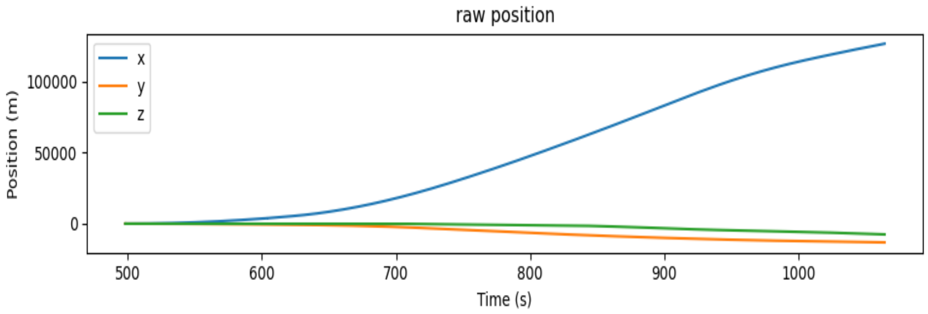


Figure 15: Positions obtained directly from input accelerations to CWA

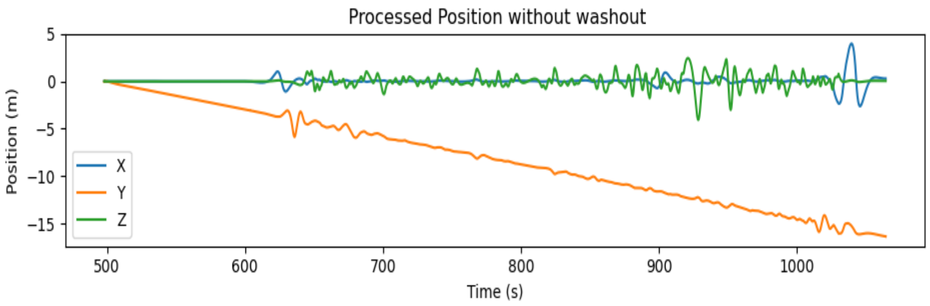


Figure 16: Positions obtained from the HP Filtered accelerations without washout damping

EVALUATION AND RESULTS
Evaluation of customised CWA

Effect of Washout Damping Factors in Translation channel

- Washout damping → Further reduces drift.
- Final position plots → Controlled pose decay confirming effective damping behavior.
- Velocity plot → Below 10 m/s limit of IPAnema 3.

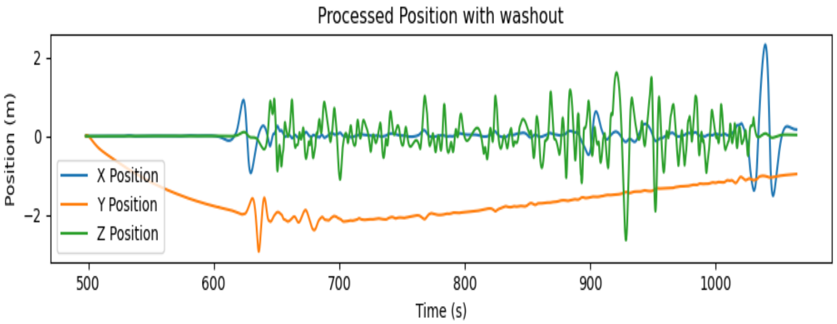


Figure 17: Final translational poses of the IPAnema 3 platform

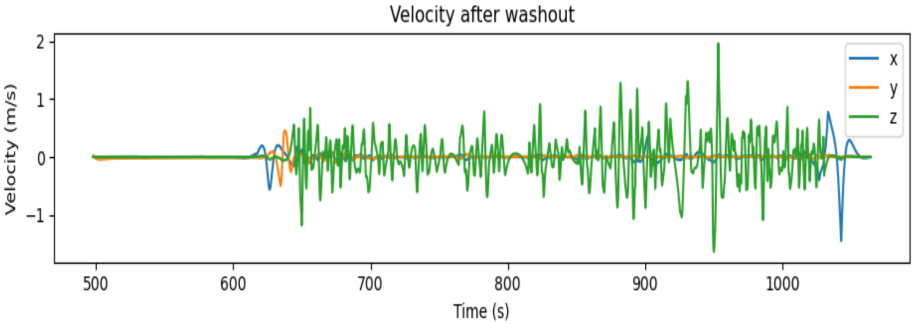


Figure 18: Final velocities of the IPAnema 3 platform

EVALUATION AND RESULTS
Evaluation of customised CWA

Effect of Cutoff Frequencies in Rotational channel:

- Trajectory had minimal rotational dynamics low → HP cut-off.
- Plots show scaled reductions.
- No significant change in rotational cue content.

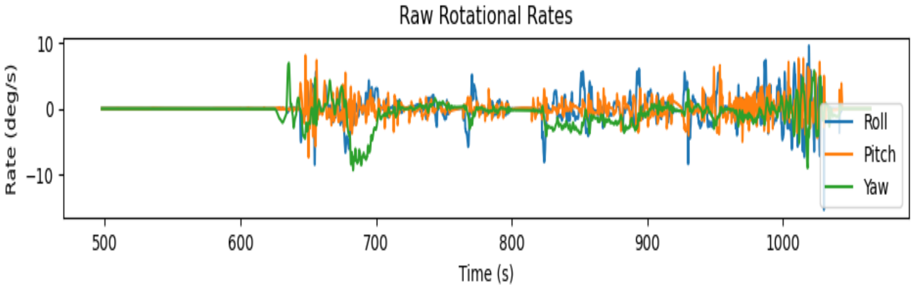


Figure 19:Input Rotational Rates to the CWA

Figure 20: Rotational Rates after HP Filtering

EVALUATION AND RESULTS
Evaluation of customised CWA

Effect of Cutoff Frequencies in Rotational channel:

- Trajectory included a 360° yaw → yaw scaling > roll/pitch.
- Yaw remained high after HP filtering → need for washout.

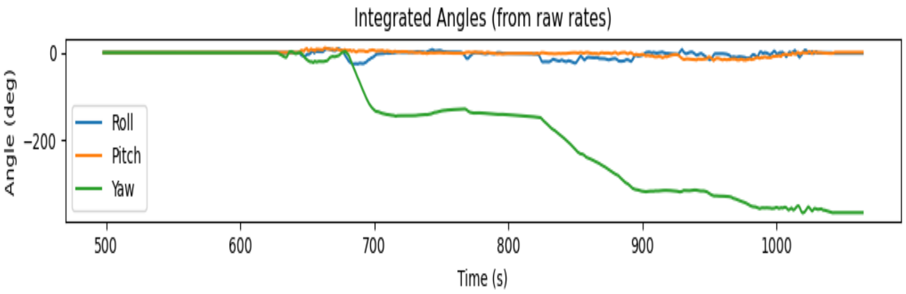


Figure 21: Rotational angles obtained directly from input rotational rates

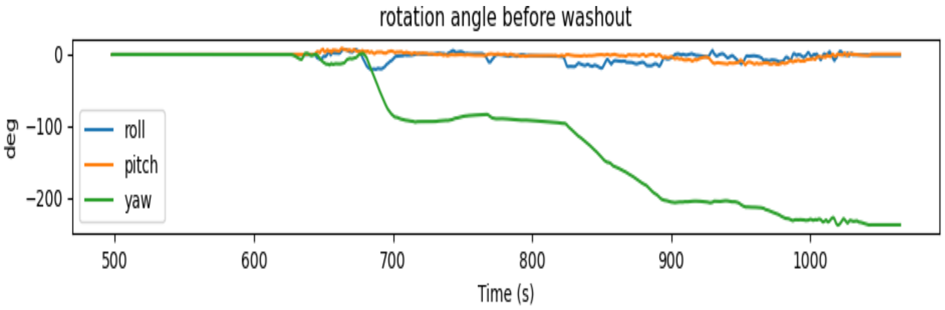


Figure 22: Rotational angles obtained from HP Filtered rotational rates without washout

EVALUATION AND RESULTS
Evaluation of customised CWA

Effect of Washout Damping Factors in Rotational channel:

- Washout damping → Ensured return to neutral position.
- Higher yaw damping → Countered large accumulated rotation.

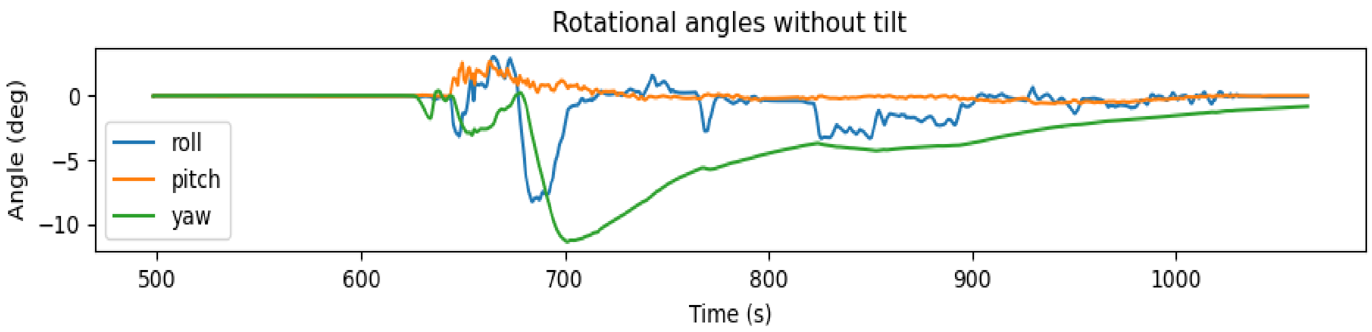


Figure 23: Washout rotational angles without tilt

EVALUATION AND RESULTS
Evaluation of customised CWA

Summing Tilt Angles in Rotational Channel

- Tilt rate < 2°/s → rate limiter not needed.
- Tilt angles summed with rotational angles (Roll and Pitch).

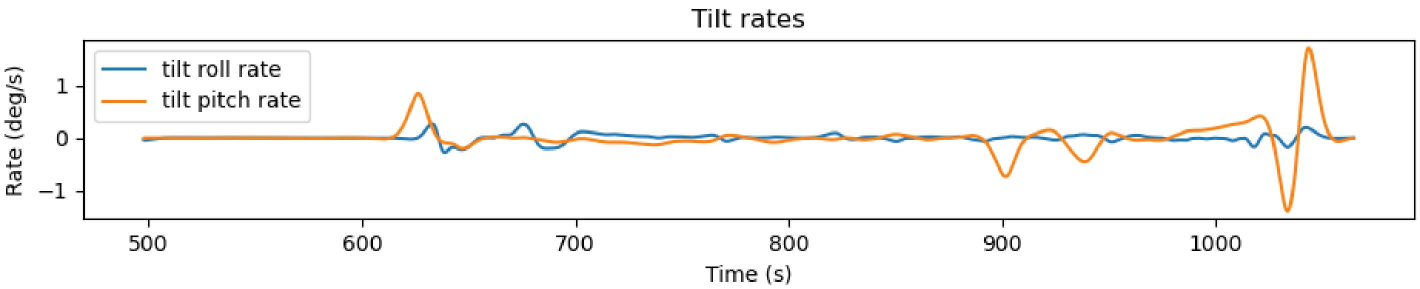


Figure 24: Tilt rates obtained from the tilt coordination channel

EVALUATION AND RESULTS
Evaluation of customised CWA

Summing Tilt Angles in Rotational Channel

- Combined plot shows influence of tilt on the final platform orientation.

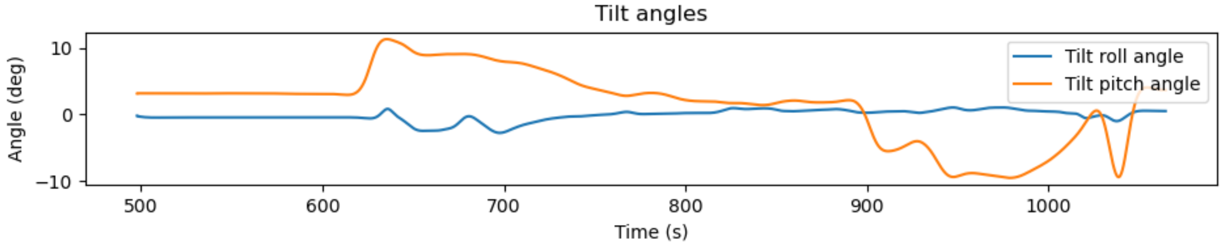


Figure 25: Tilt angles obtained from the tilt coordination channel

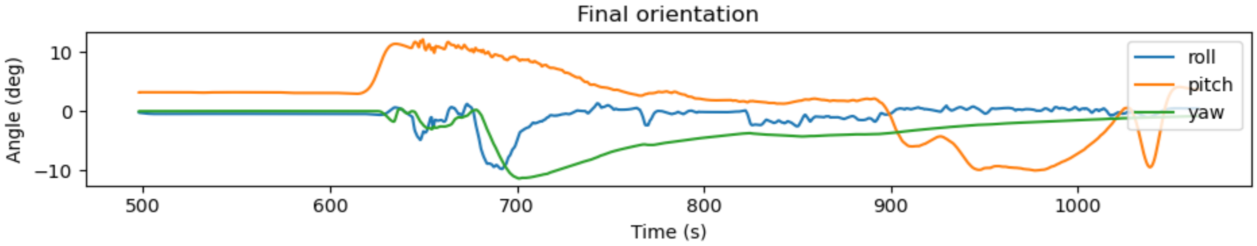


Figure 26: The final orientation of the IPAnema 3 platform

EVALUATION AND RESULTS
Evaluation of Cost Function Optimisation

Force Factors as Cost Metric

- Objective: Match platform (output) forces with simulated (input) forces.
- Clear deviations during dynamic events (like landing).
- Deviations caused by filtering, damping, and scaling.
- Overall force trends are preserved.

EVALUATION AND RESULTS
Evaluation of Cost Function Optimisation

Force Factors as Cost Metric

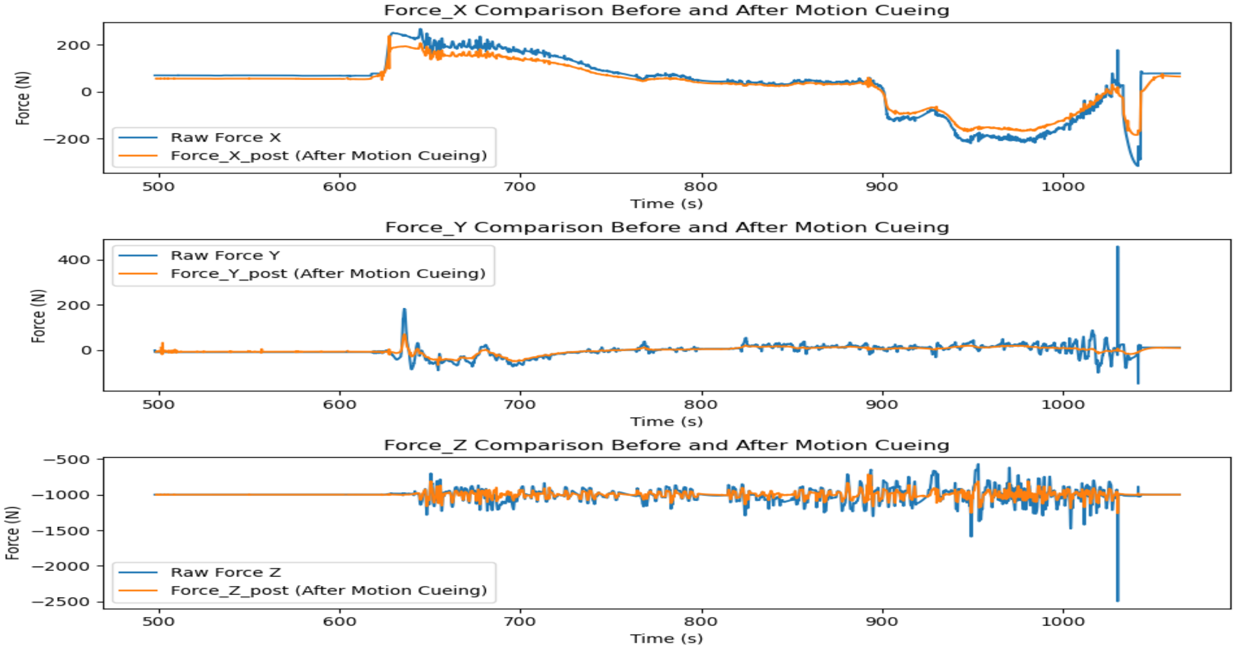


Figure 27: Comparison of input forces to the forces acting on the platform

EVALUATION AND RESULTS
Evaluation of Cost Function Optimisation

Outlier Mitigation through Normalisation

- RAE-based Force Factor showed extreme outliers.
- Outliers distorted the mean cost.
- 5 N offset → More stable cost function.

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Outlier Mitigation through Normalisation

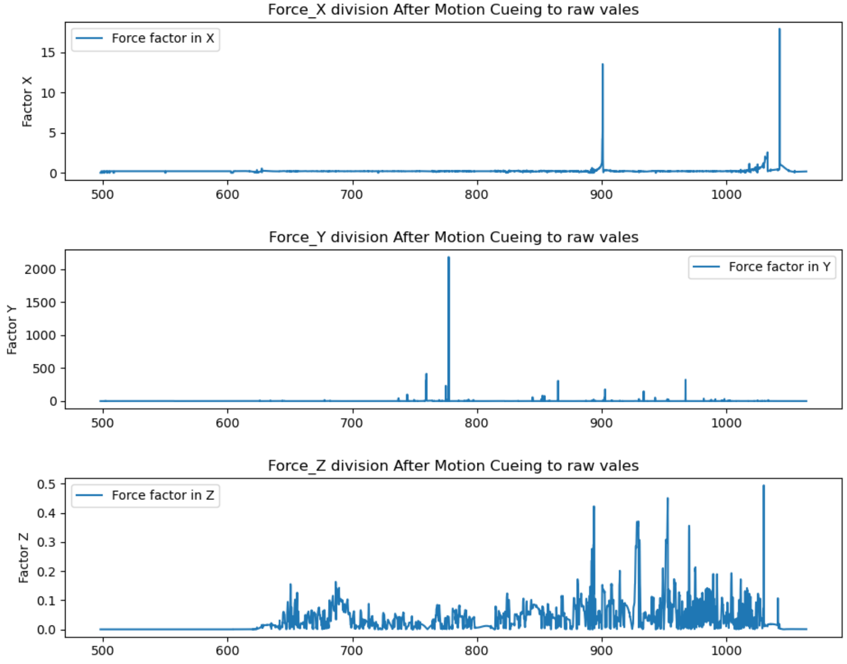

Figure 28: Force Factors without Offset

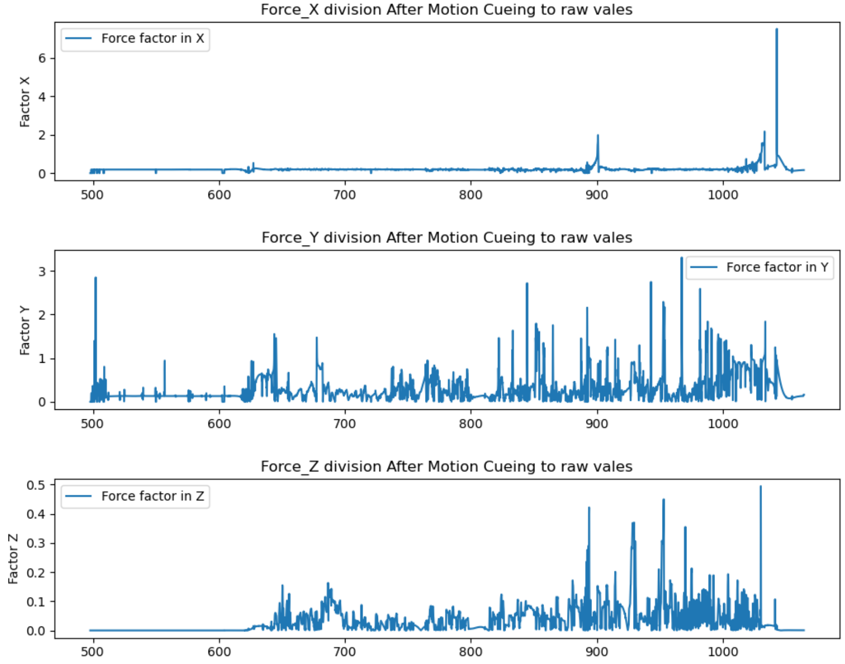

Figure 29: Force Factors with Offset

EVALUATION AND RESULTS
Evaluation of Cost Function Optimisation

Cost Function Optimisation Results

Table 1: Force factors and washout damping factors

Axis	Average force factors/cost (manual tuning)	Average force factors/cost (post optimisation)	Manual washout damping factors (translational)	Optimised washout damping factors (translational)
X	0.2101	0.2271	0.001	0.00470148
Y	0.3002	0.2971	0.005	0.00470148
Z	0.0345	0.0505	0.001	0.00470153

- Multi-Axis optimisation trade-offs.
- Effect of strong manual tuning.

Cost Function Optimisation Results

- Improved Force Stability

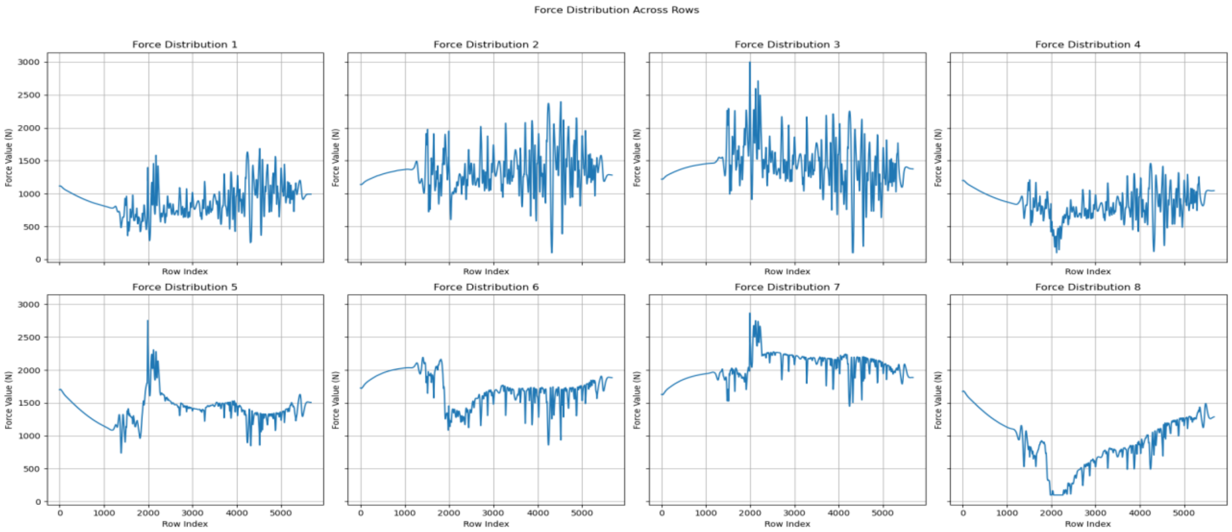

Figure 30: Force distribution on cables before optimisation

EVALUATION AND RESULTS
Evaluation of Cost Function Optimisation

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Cost Function Optimisation Results

- Improved Force Stability

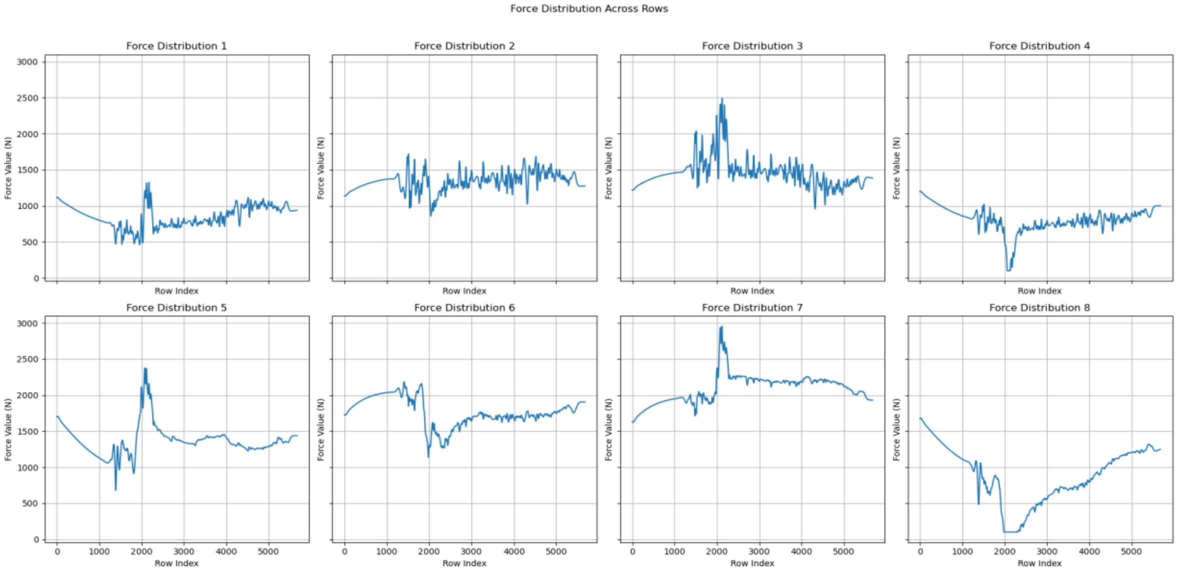

Figure 31: Force distribution on cables after optimisation

EVALUATION AND RESULTS
Evaluation on Dynamic Trajectory

Table 2: Force factors and washout damping factors for dynamic trajecory

Axis	**Average force factors/cost (manual tuning)**	**Average force factors/cost (post optimisation)**	**Manual washout damping factors (translational)**	**Optimised washout damping factors (translational)**
X	0.2176	0.2351	0.001	0.00482051
Y	0.5563	0.5527	0.005	0.00482051
Z	0.2850	0.2826	0.005	0.00482056

- Higher Z and Yaw manual damping.
- Higher force factors in Y and Z axes.

EVALUATION AND RESULTS
Evaluation on High Payload

- Z-axis force → -2400 N (~245 kg payload - IPAnema 3’s max capacity)

Table 3: Force factors and washout damping factors for high payload

Axis	Average force factors/cost (manual tuning)	Average force factors/cost (post optimisation)	Manual washout damping factors (translational)	Optimised washout damping factors (translational)
X	0.2300	0.2361	0.002	0.00307043
Y	0.4010	0.3514	0.006	0.00307043
Z	0.0410	0.0459	0.002	0.00307049

- Higher initial manual damping.
- Reduced effective workspace.

EVALUATION AND RESULTS
Comparision

Table 4: Comparison of final parameters

Trajectory type	Manual damping [X, Y, Z]	Optimised damping [X, Y, Z]	Manual damping [roll, pitch, yaw]	Manual average force factor [X, Y, Z]	Optimised average force factor [X, Y, Z]
Trajectory 1 with Z = -1000N	[0.001, 0.005, 0.001]	[0.00470148, 0.00470148, 0.00470153]	[0.005, 0.007, 0.01]	[0.2101, 0.3002, 0.0345]	[0.2271, 0.2971, 0.0505]
Trajectory 2 with Z = -1000N	[0.001, 0.005, 0.005]	[0.00482051, 0.00482051, 0.00482056]	[0.005, 0.007, 0.018]	[0.2176, 0.5563, 0.2850]	[0.2351, 0.5527, 0.2826]
Trajectory 1 With Z = -2400N	[0.002, 0.006, 0.002]	[0.00307043, 0.00307043, 0.00307049]	[0.006, 0.008, 0.02]	[0.2300, 0.4010, 0.0410]	[0.2361, 0.3514, 0.0459]

CONCLUSION AND OUTLOOK

CONCLUSION AND OUTLOOK
Summary

- Demonstrated a systematic, force feasible approach for motion cueing using CWA for the CDPR IPAnema 3 platform.
- Introduced a cost function optimization to this CWA.
- Results → Modest improvements in cost but improved force stability.

CONCLUSION AND OUTLOOK

Future work

- Hardware Implementation.
- Optimisation of rotational parameters.
- Axis-Wise independent optimization.
- Adaptive platform orientation and origin shifting.
- Real time optimisation.
- Generalisation to other CDPR systems.

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THANK YOU ☺

Open for questions