PPMEC | Pós-Graduação em Sistemas Mecatrônicos
Faculdade de Tecnologia
Departamento de Engenharia Mecânica

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# Development of the Linear Delta Robot for Additive Manufacturing


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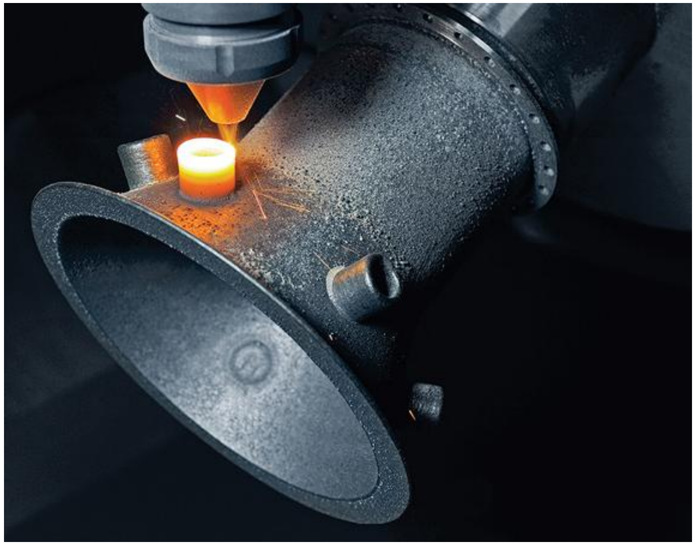
# Summary

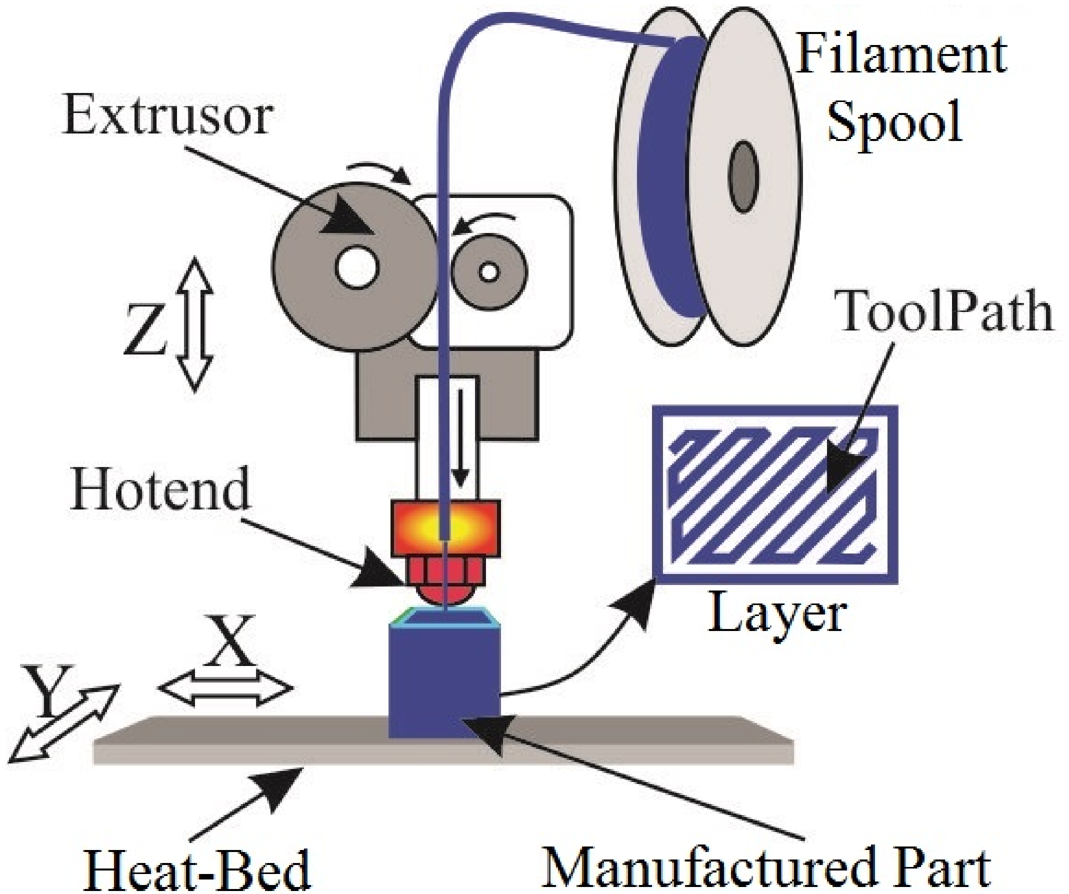
- Preamble: Additive Manufacturing (AM) and Delta Robot
- Design methology based on Quality Function Deployment (QFD)
- Modeling and kinematic analysis of the linear delta robot
- Dimensional optimization of the linear delta robot
- Results, validation prototype and demostrative video
- Conclusions

# Additive Manufacturing (AM)

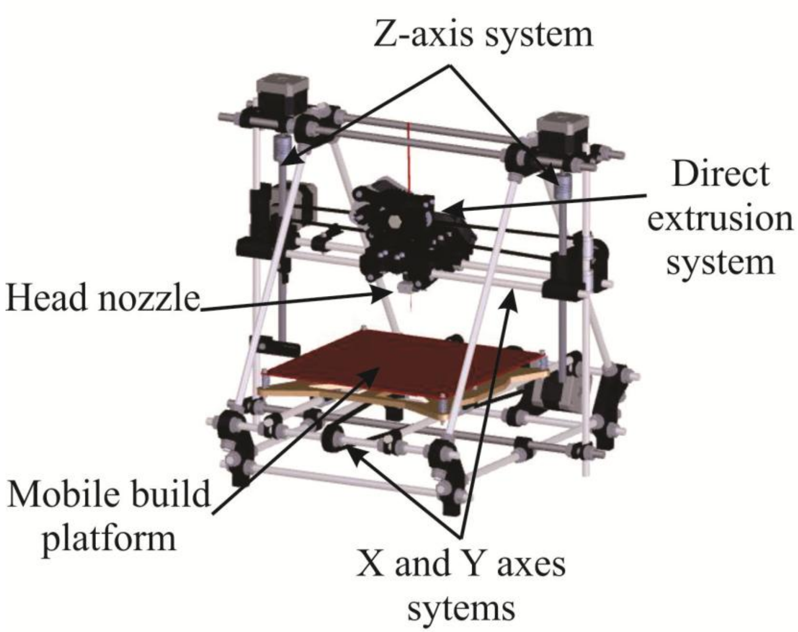
- Manufacturing of physical objects with complex geometries.
- Reduced time-to-launch of new products.
- Mass customization.
- Improvements in the supply chain.
- Does not need expensive tools.



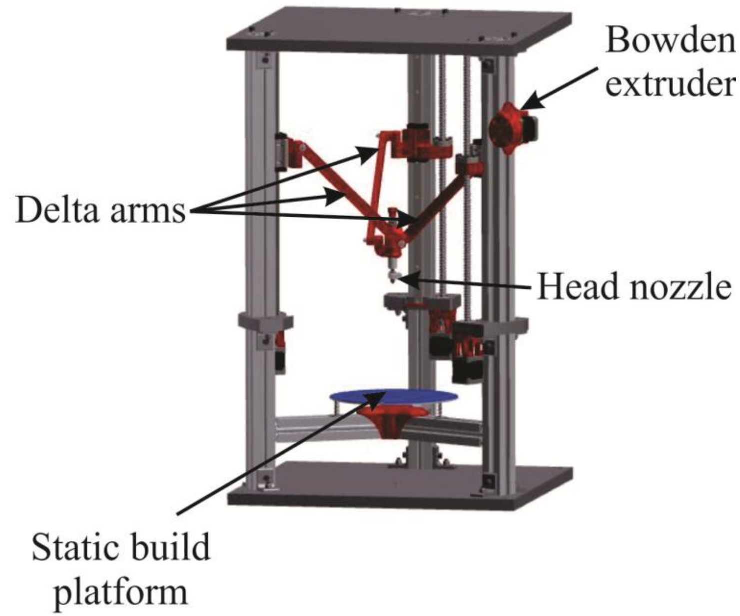
# Fused Deposition Modeling (FDM) process



# Comparison of FDM architecture

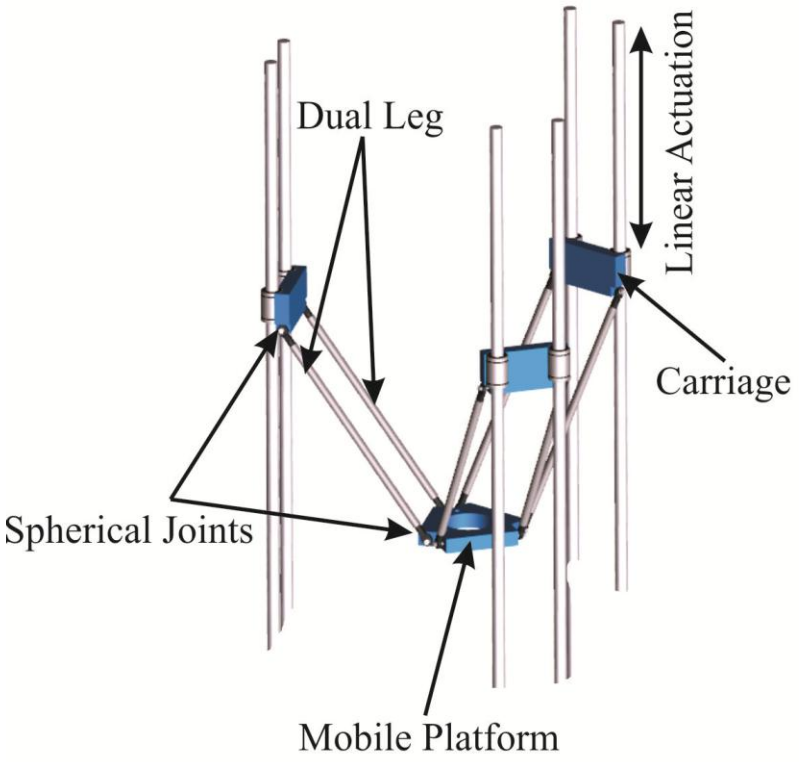



Cartesian Structure

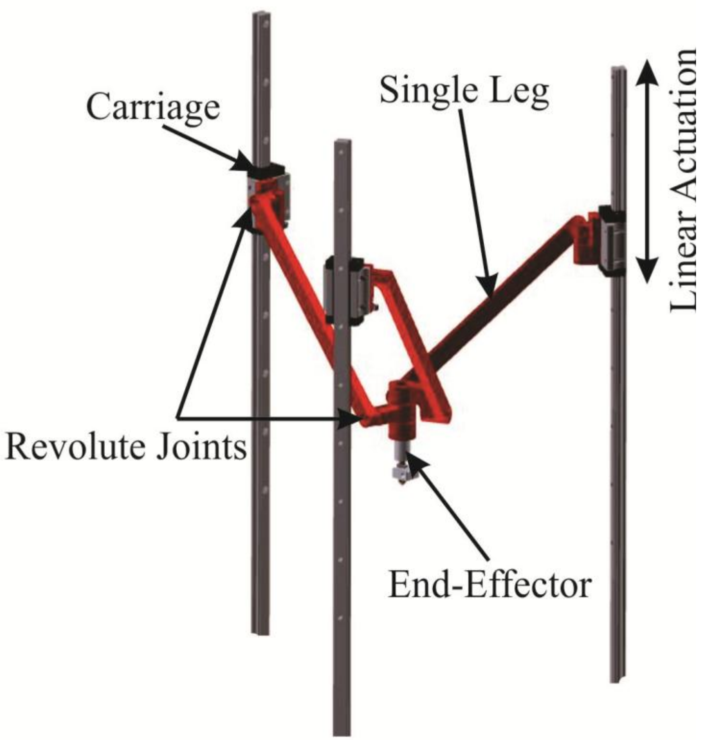



Linear Delta Structure

# Comparasion of the new linear delta mechanism




Delta with dual legs




Proposed Delta with single legs

# Comparison of different Linear Delta robot Structure for FDM

Table 1: Comparison of different Linear Delta robot structure for FDM

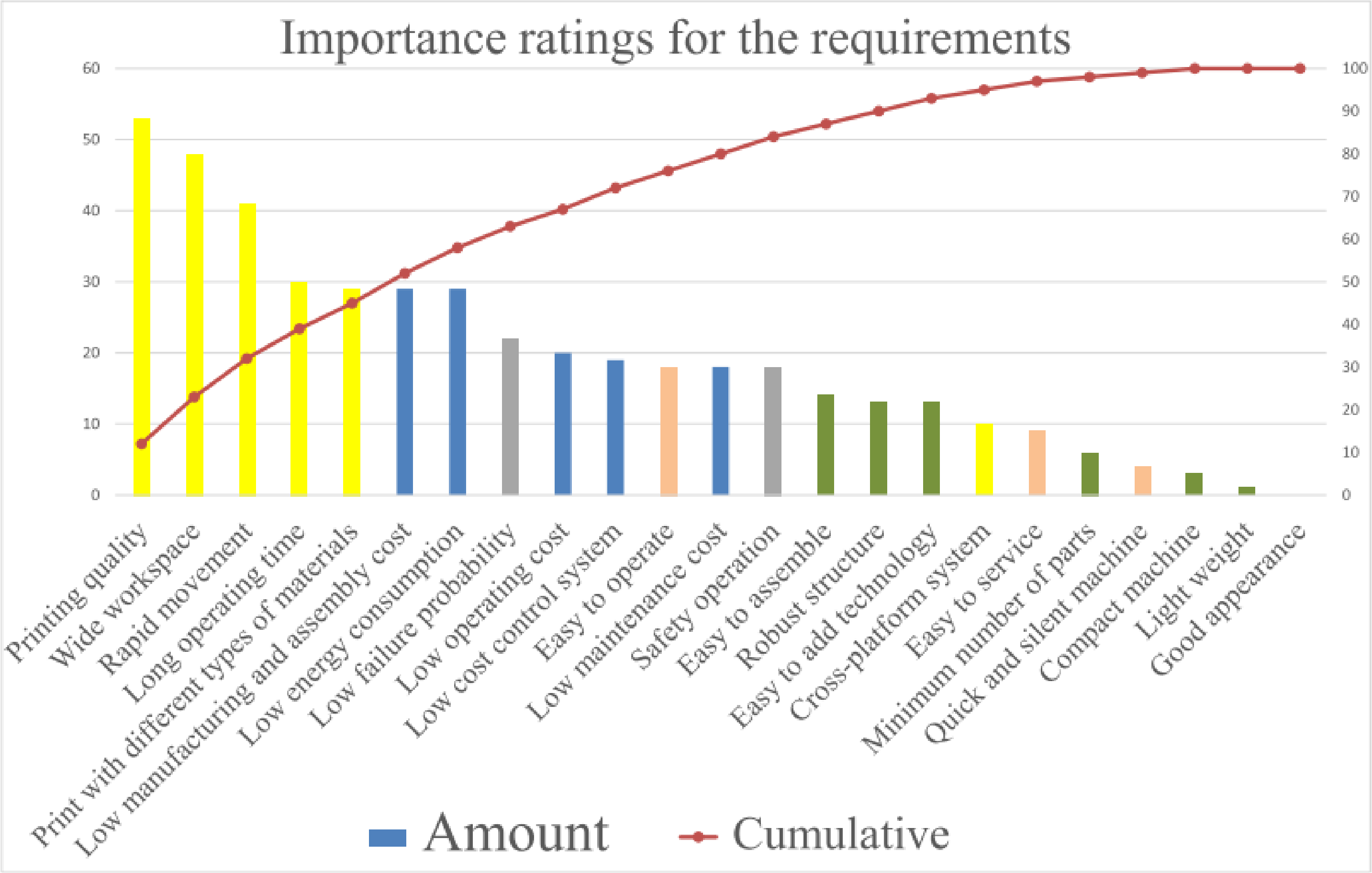
| | Linear Delta I (3 dual legs, 12 ball joints) | Linear Delta II (3 single legs, 6 cardans) | Linear Delta III (3 single legs, 11 revolute joints) |
|---|---|---|---|
| Cost | -/+ | - | ++ |
| Workspace | – | - | + |
| Speed | -/+ | + | + |
| Inertia | - | + | ++ |
| Stiffness | ++ | + | - |
| Accuracy | + | + | + |
| Assemblage simplicity | - | - | ++ |

Note: much bigger (++), bigger (+), medium (+/-) and smaller (-)

# Defined user requirements (URs) or "What's"

| Categories | User Requirements |
|---|---|
| 1. Capacity | 1.1-Printing quality; 1.2-Rapid movement; 1.3-Long operating time; 1.4-Wide workspace; 1.5-Cross-platform system; 1.6-Print with different types of materials |
| 2. Operation | 2.1-Easy to operate; 2.2- Quick and silent machine; |
| 3. Design | 3.1-Compact machine; 3.2-Robust structure; 3.3-Light weight; 3.4-Minimum number of parts; 3.5-Easy to assemble; 3.6-Good appearance; 3.7-Easy to add technology |
| 4. Economy | 4.1-Low manufacturing and assembly cost; 4.2-Low operating cost; 4.3-Low energy consumption; 4.4-Low cost control system; 4.5-Low maintenance cost |
| 5. Reliability | 5.1-Safety operation; 5.2-Low failure probability |

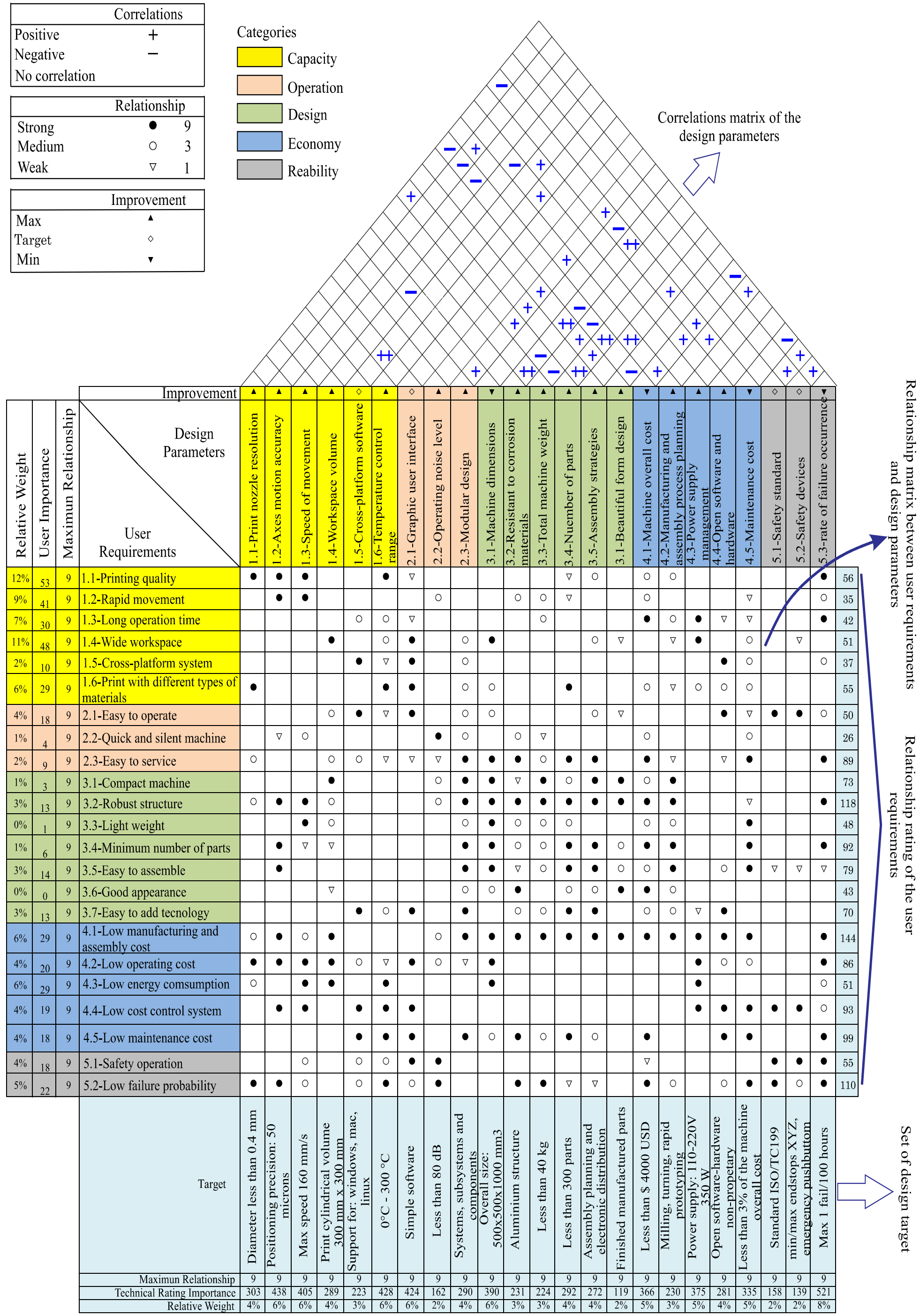
# Average importance ratings for the user requirements shown in the Pareto chart



# Selected design parameters (DPs) or "How's"

| Categories | Design parameters |
|---|---|
| 1. Capacity | 1.1-Resolution of the print nozzle; 1.2-Axes motion accuracy; 1.3-Speed of movement; 1.4-Workspace volume; 1.5-Cross-platform software; 1.6-Temperature control range |
| 2. Operation | 2.1-Graphic user interface; 2.2-Operating noise level; 2.3-Modular design |
| 3. Design | 3.1-Machine dimensions; 3.2-Use resistant to corrosion material; 3.3- Total weight of the machine; 3.4-Number of parts; 3.5-Assembly strategies; 3.6-Beautiful form design; |
| 4. Economy | 4.1- Machine overall cost; 4.2-Manufacturing and assembly process planning; 4.3-Power supply management; 4.4-Open-source and open-hardware technology; 4.5-Maintenance cost |
| 5. Reliability | 5.1-Safety standards; 5.2-Safety devices; 5.3-Rate of occurrence of failure |

# QFD – House of Quality



# QFD matrix of relationship between RUs and DPs

Categories

- Capacity
- Operation
- Design
- Economy
- Reability

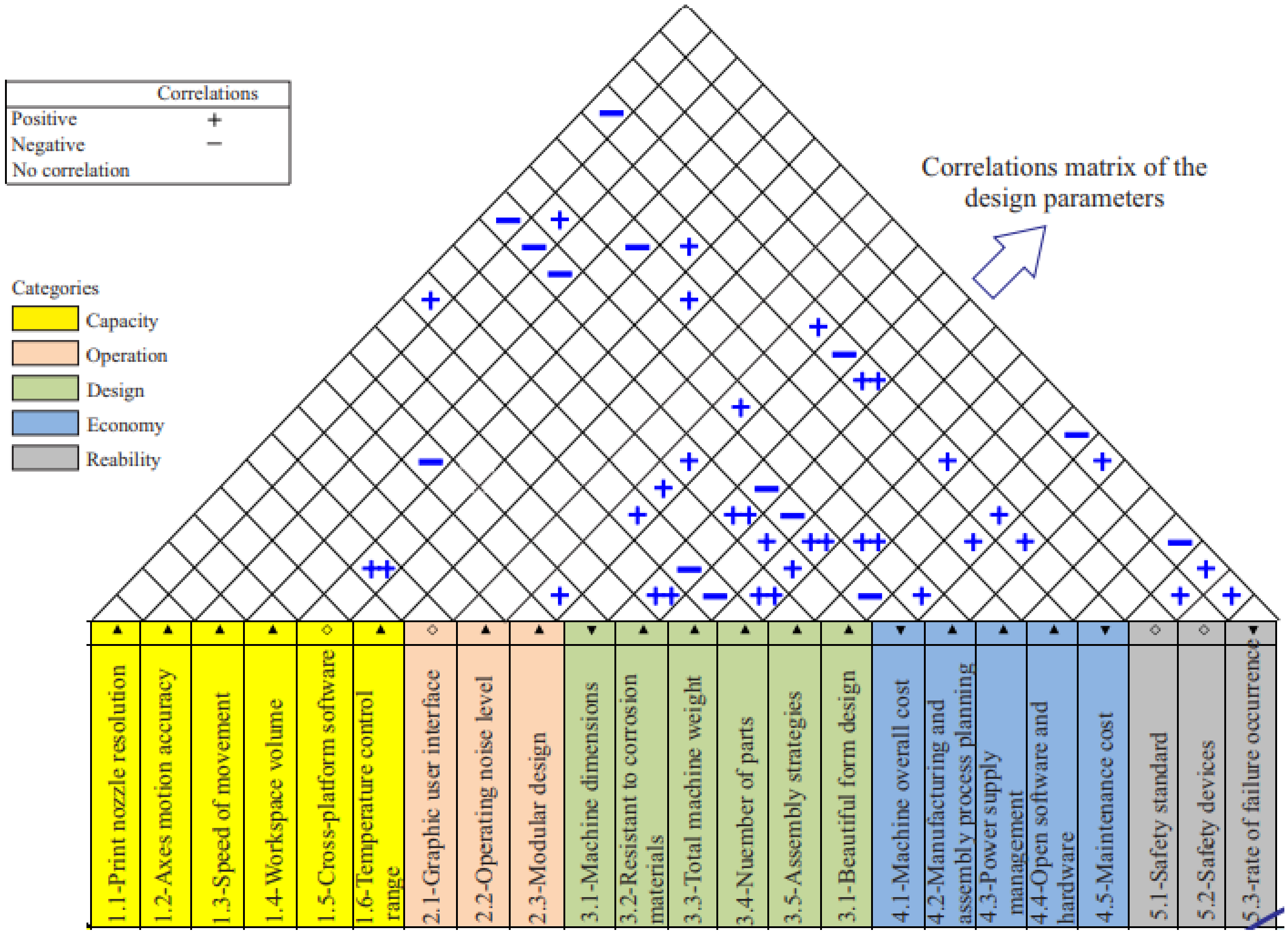
| Relationship | | |
|---|---|---|
| Strong | ● | 9 |
| Medium | ○ | 3 |
| Weak | ▽ | 1 |

| Relative Weight | User Importance | Maximum Relationship | Design Parameters / User Requirements | 1.1-Print nozzle resolution | 1.2-Axes motion accuracy | 1.3-Speed of movement | 1.4-Workspace volume | 1.5-Cross-platform software | 1.6-Temperature control range | 2.1-Graphic user interface | 2.2-Operating noise level | 2.3-Modular design | 3.1-Machine dimensions | 3.2-Resistant to corrosion materials | 3.3-Total machine weight | 3.4-Nuember of parts | 3.5-Assembly strategies | 3.1-Beautiful form design | 4.1-Machine overall cost | 4.2-Manufacturing and assembly process planning | 4.3-Power supply management | 4.4-Open software and hardware | 4.5-Maintenance cost | 5.1-Safety standard | 5.2-Safety devices | 5.3-rate of failure occurrence | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Improvement | ▲ | ▲ | ▲ | ▲ | ◇ | ▲ | ◇ | ▲ | ▲ | ▼ | ▲ | ▲ | ▲ | ▲ | ▲ | ▼ | ▲ | ▲ | ▲ | ▼ | ◇ | ◇ | ▼ | |
| 12% | 53 | 9 | 1.1-Printing quality | ● | ● | ● | | | ● | ▽ | | | | | | ▽ | ○ | | ○ | ○ | | | | | | ● | 56 |
| 9% | 41 | 9 | 1.2-Rapid movement | | ● | ● | | | | | ○ | | | ○ | ○ | ▽ | | | ○ | | | | ▽ | | | ○ | 35 |
| 7% | 30 | 9 | 1.3-Long operation time | | | | | ○ | ○ | ▽ | | | | | ○ | | | | ● | ○ | ● | ▽ | ▽ | | | ● | 42 |
| 11% | 48 | 9 | 1.4-Wide workspace | | | | ● | | ○ | ● | | ○ | ● | | | | ○ | ▽ | | ▽ | ● | | ○ | | ▽ | | 51 |
| 2% | 10 | 9 | 1.5-Cross-platform system | | | | | ● | ▽ | ● | | ○ | | | | | | | | | | ● | ○ | | | ○ | 37 |
| 6% | 29 | 9 | 1.6-Print with different types of materials | ● | | | | | ● | ● | | ○ | ○ | | | ● | | | ○ | ▽ | ○ | ○ | ○ | | | | 55 |
| 4% | 18 | 9 | 2.1-Easy to operate | | | | ○ | ● | ▽ | ● | | ○ | ○ | | | | ○ | ▽ | | | | ● | ▽ | ● | ● | ○ | 50 |
| 1% | 4 | 9 | 2.2-Quick and silent machine | | ▽ | ○ | | | | | ● | ○ | | ○ | ▽ | | | | ○ | | | | ○ | | | | 26 |
| 2% | 9 | 9 | 2.3-Easy to service | ○ | | | ○ | ○ | ▽ | ▽ | ▽ | ● | ● | ● | ○ | ● | ● | | ● | ▽ | | ▽ | ● | | | ● | 89 |
| 1% | 3 | 9 | 3.1-Compact machine | | | | ● | | | | ○ | ● | ● | ▽ | ● | ○ | ● | ● | ○ | ● | | | | | | | 73 |
| 3% | 13 | 9 | 3.2-Robust structure | ○ | ● | ● | ○ | | | | ○ | ● | ● | ● | ● | ● | ● | ● | ● | ● | | | ▽ | | | ● | 118 |
| 0% | 1 | 9 | 3.3-Light weight | | | ● | ○ | | | | | ○ | ● | ○ | ○ | ○ | | | ○ | ○ | | | ● | | | | 48 |
| 1% | 6 | 9 | 3.4-Minimum number of parts | | ● | ▽ | ▽ | | | | | ● | ● | ○ | ○ | ● | ● | ○ | ● | ● | | | ● | | | ● | 92 |
| 3% | 14 | 9 | 3.5-Easy to assemble | | ● | | | | | | | ● | ● | ▽ | ○ | ● | ● | ○ | ○ | ● | | ○ | ● | ▽ | ▽ | ▽ | 79 |
| 0% | 0 | 9 | 3.6-Good appearance | | | | ▽ | | | | | ○ | ○ | ● | | ○ | ○ | ● | ● | ○ | | | | | | | 43 |
| 3% | 13 | 9 | 3.7-Easy to add tecnology | | | | | ● | ○ | ● | | ● | | ○ | ○ | ● | ● | | ○ | ○ | ▽ | ● | | | | | 70 |
| 6% | 29 | 9 | 4.1-Low manufacturing and assembly cost | ○ | ● | ○ | ● | | | | ○ | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | | | ● | 144 |
| 4% | 20 | 9 | 4.2-Low operating cost | ● | ● | ● | ● | ○ | ▽ | ● | ○ | ▽ | ● | | | | | | | | ● | ○ | ○ | | | ● | 86 |
| 6% | 29 | 9 | 4.3-Low energy comsumption | ○ | | ● | ● | | ● | | | | ● | | | | | | | | ● | | | | | ○ | 51 |
| 4% | 19 | 9 | 4.4-Low cost control system | | ● | ● | | ● | ● | ● | | | | | | | | | | | ● | ● | ● | ● | ● | ○ | 93 |
| 4% | 18 | 9 | 4.5-Low maintenance cost | | | | | ● | ● | ● | | ● | ○ | ● | ○ | ● | ○ | | ● | | | ● | ● | | | ● | 99 |
| 4% | 18 | 9 | 5.1-Safety operation | | | ○ | | ○ | ○ | ● | ● | | | | | | | | ▽ | | | | | ● | ● | ● | 55 |
| 5% | 22 | 9 | 5.2-Low failure probability | ● | ● | ○ | | ○ | ● | ○ | ● | | | ● | ● | ▽ | ▽ | | ● | ○ | | ○ | ● | ● | ○ | ● | 110 |

Relationship matrix between user requirements and design parameters

Relationship rating of the user requirements

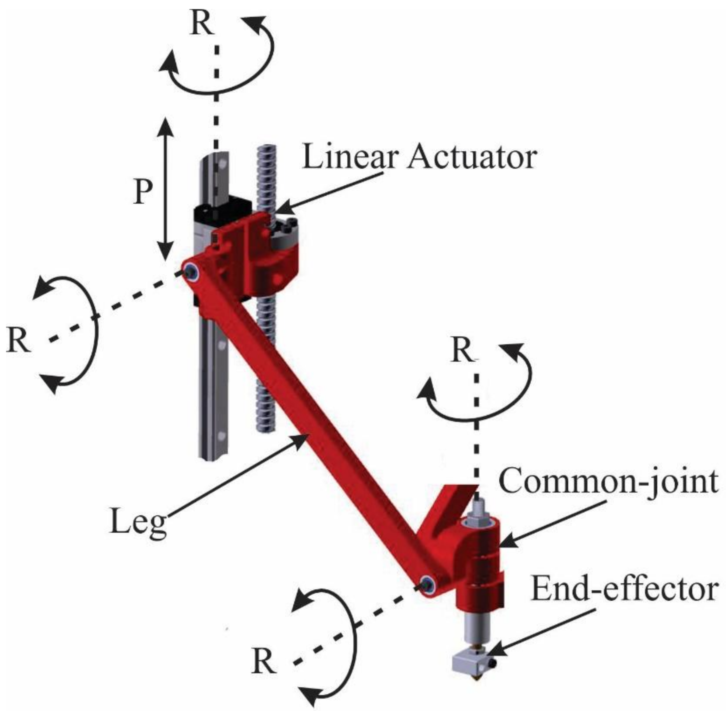
# Matrix of correlations between DPs

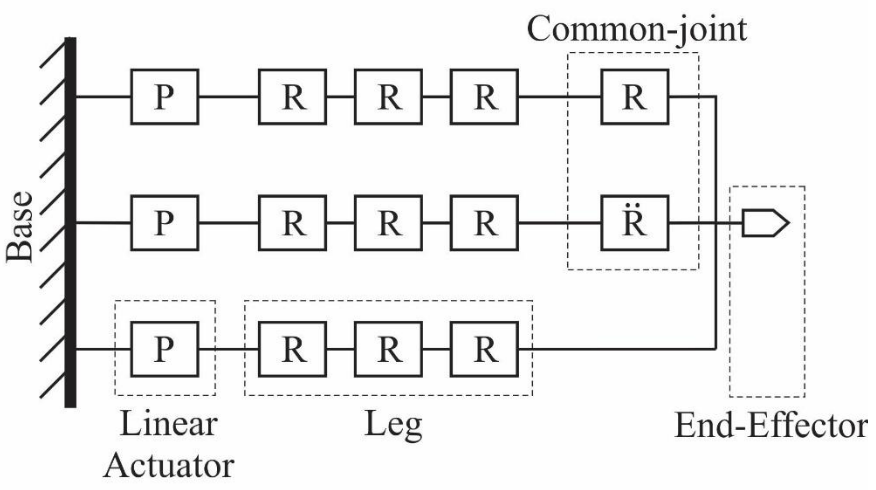


# Specifications-meta for the linear delta robot

| | | | | |
|---|---|---|---|---|
| 4% | 303 | 9 | Diameter less than 0.4 mm | 1.1-Print nozzle resolution |
| 6% | 438 | 9 | Positioning precision: 50 microns | 1.2-Axes motion accuracy |
| 6% | 405 | 9 | Max speed 160 mm/s | 1.3-Speed of movement |
| 4% | 289 | 9 | Print cylindrical volume 300 mm x 300 mm | 1.4-Workspace volume |
| 3% | 223 | 9 | Support for: windows, mac, linux | 1.5-Cross-platform software |
| 6% | 428 | 9 | 0°C - 300 °C | 1.6-Temperature control range |
| 6% | 424 | 9 | Simple software | 2.1-Graphic user interface |
| 2% | 162 | 9 | Less than 80 dB | 2.2-Operating noise level |
| 4% | 290 | 9 | Systems, subsystems and components | 2.3-Modular design |
| 6% | 390 | 9 | Overall size: 500x500x1000 mm3 | 3.1-Machine dimensions |
| 3% | 231 | 9 | Aluminium structure | 3.2-Resistant to corrosion materials |
| 3% | 224 | 9 | Less than 40 kg | 3.3-Total machine weight |
| 4% | 292 | 9 | Less than 300 parts | 3.4-Nuember of parts |
| 4% | 272 | 9 | Assembly planning and electronic distribution | 3.5-Assembly strategies |
| 2% | 119 | 9 | Finished manufactured parts | 3.1-Beautiful form design |
| 5% | 366 | 9 | Less than $ 4000 USD | 4.1-Machine overall cost |
| 3% | 230 | 9 | Milling, turning, rapid prototyping | 4.2-Manufacturing and assembly process planning |
| 5% | 375 | 9 | Power supply: 110-220V 350 W | 4.3-Power supply management |
| 4% | 281 | 9 | Open software-hardware non-propetary | 4.4-Open software and hardware |
| 5% | 335 | 9 | Less than 3% of the machine overall cost | 4.5-Maintenance cost |
| 2% | 158 | 9 | Standard ISO/TC199 | 5.1-Safety standard |
| 2% | 139 | 9 | min/max endstops XYZ, emergency pushbuttom | 5.2-Safety devices |
| 8% | 521 | 9 | Max 1 fail/100 hours | 5.3-rate of failure occurrence |

# Kinematics model and mobility analysis

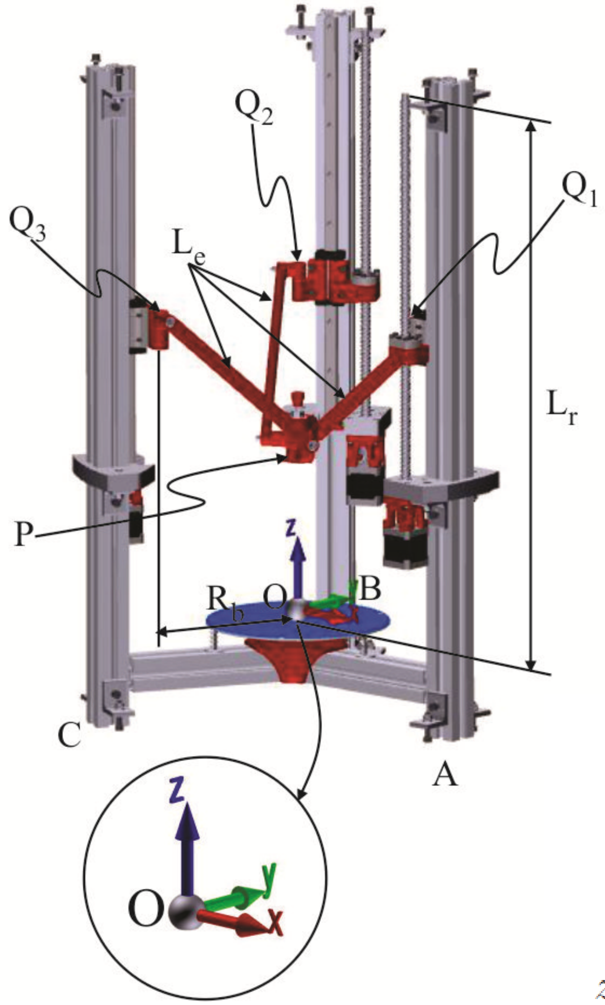


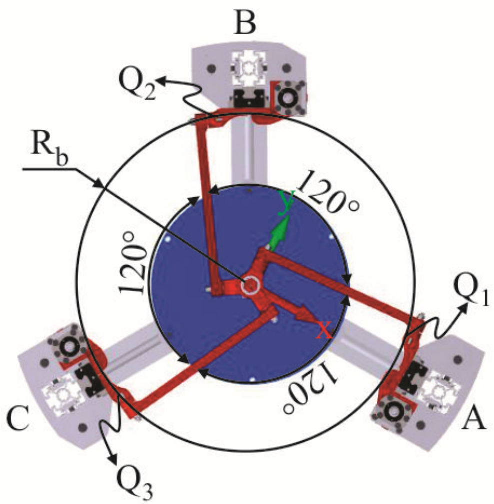




P: prismatic joints
R: revolute joints
Ř: revolute joint with two DOF

$$M = 6(12) - \sum_{i=1}^{13}(6-1) - \sum_{i=1}^{1}(6-2) = 72 - 13(5) - 1(4) = 3$$

# Inverse Kinematics



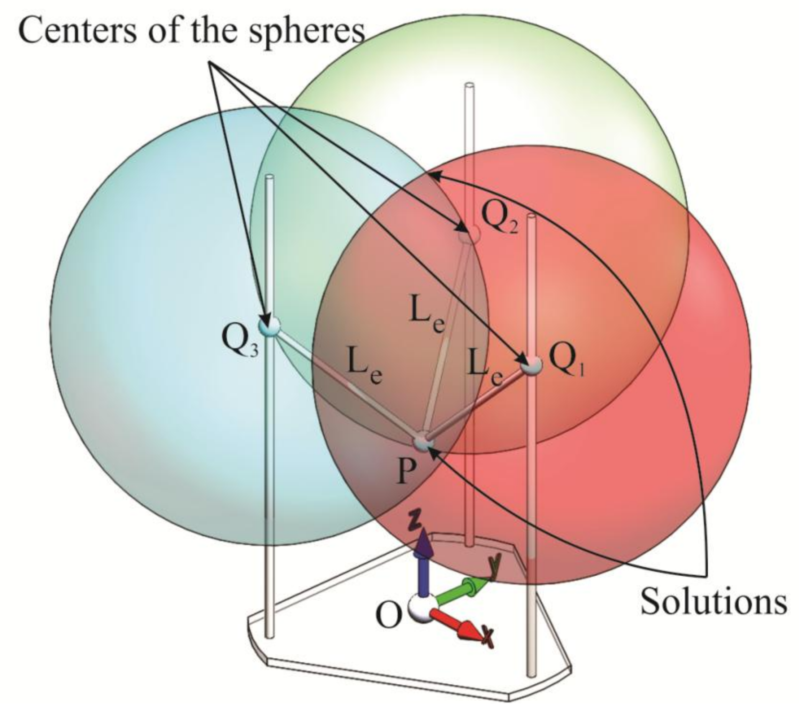

Top view - Frame XY

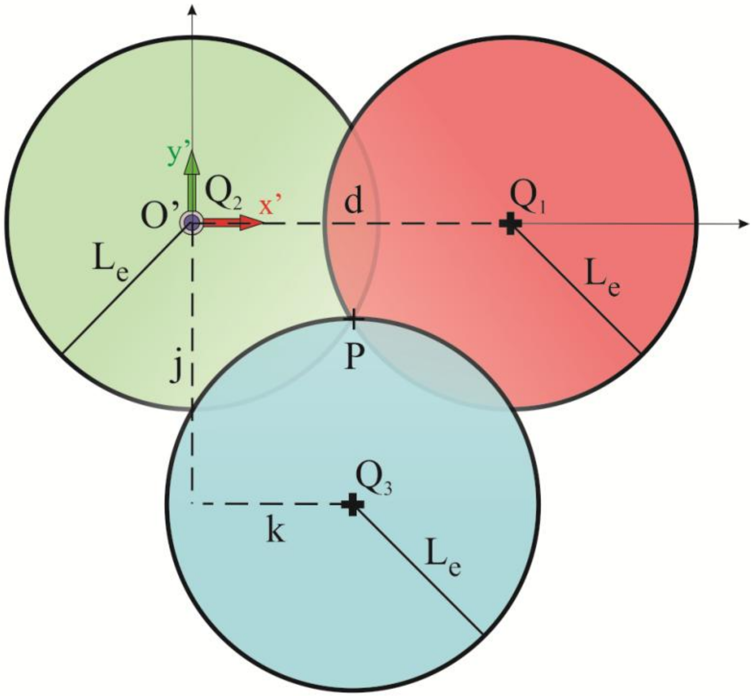
$$x_i = R_b\, cos\theta_i, \quad y_i = R_b\, sin\theta_i, \quad i = 1, 2, 3,$$

$$\theta_i = \frac{2i - 2}{3}\pi, \quad i = 1, 2, 3,$$

$$z_i = z \pm \sqrt{L_e^2 - (x - x_i)^2 - (y - y_i)^2}, \quad i = 1, 2, 3,$$

# Direct Kinematics




$$(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2 = L_e^2, \quad i = 1, 2, 3,$$

Trilateration method

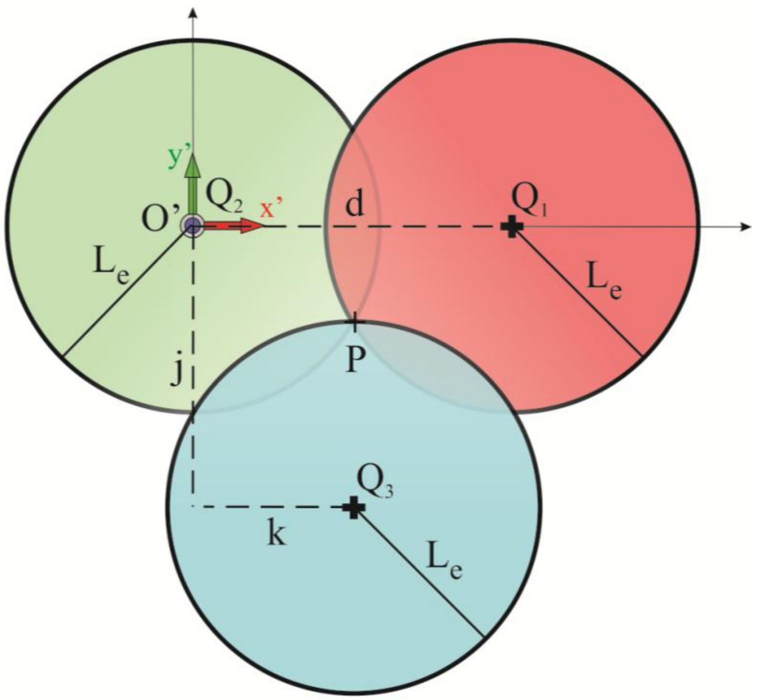
# Direct Kinematics

$$L_e^2 = x'^2 + y'^2 + z'^2$$
$$L_e^2 = (x' - d)^2 + y'^2 + z'^2$$
$$L_e^2 = (x' - k)^2 + (y' - j)^2 + z'^2$$

$$x' = \frac{1}{2}d$$

$$y' = \frac{k^2 + j^2}{2j} - \frac{k}{j}x$$

$$z' = \pm\sqrt{L_e^2 - x^2 - y^2}$$




Trilateration method

# Direct Kinematics

$$k = \hat{e}_x \cdot (Q_3 - Q_2)$$

$$\hat{e}_x = \frac{Q_1 - Q_2}{||Q_1 - Q_2||}$$

$$d = ||Q_1 - Q_2||$$

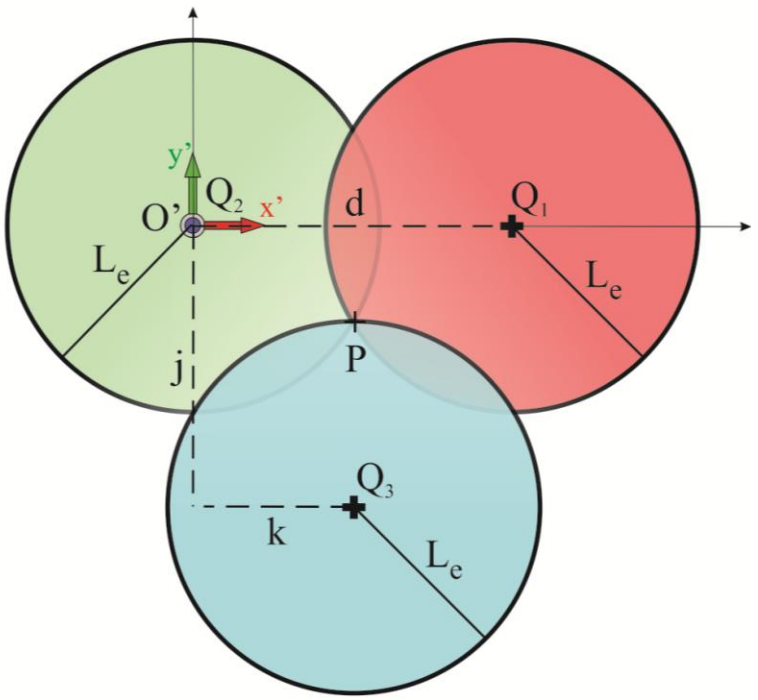
$$\hat{e}_y = \frac{Q_3 - Q_2 - k\hat{e}_x}{||Q_3 - Q_2 - i\hat{e}_x||}$$

$$j = \hat{e}_y \cdot (Q_3 - Q_2)$$

$$\hat{e}_z = \hat{e}_x \times \hat{e}_y.$$

Solutions

$$\vec{p}_{1,2} = Q_2 + x\hat{e}_x + y\hat{e}_y \pm z\hat{e}_z$$

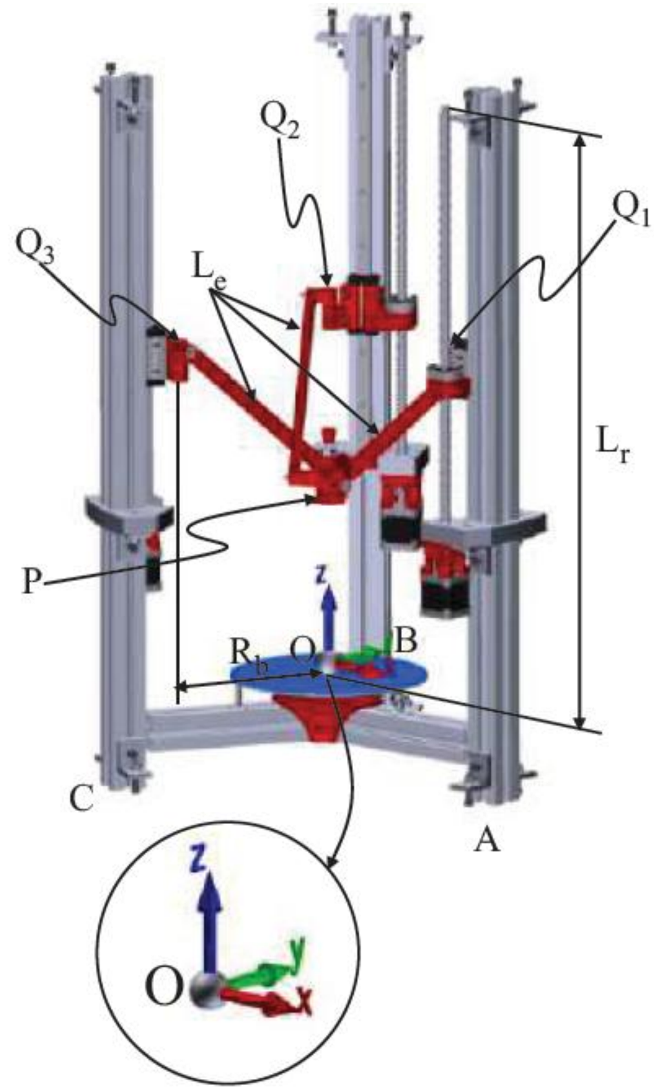



Trilateration method

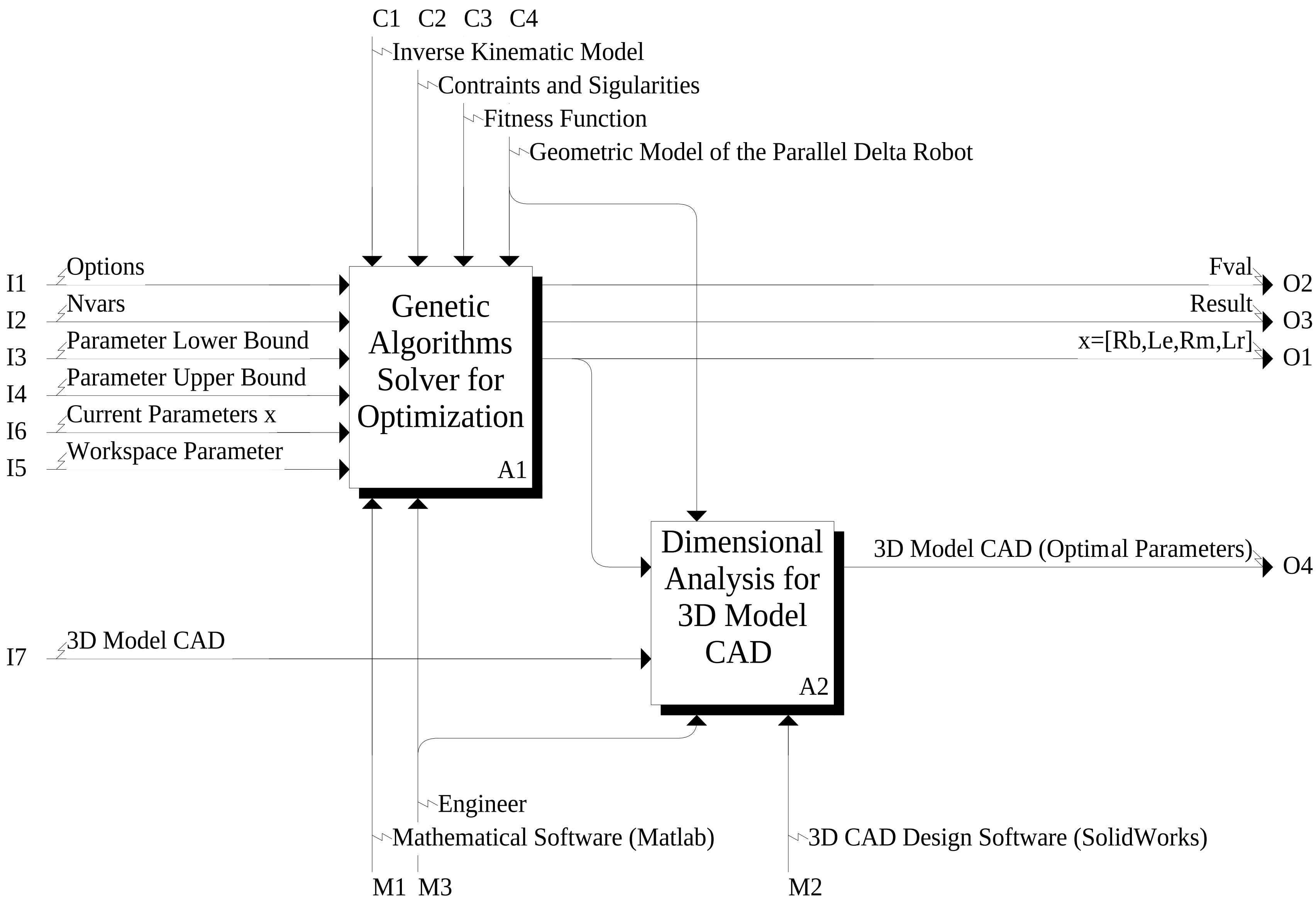
# Dimensional optimization with genetic algorithm

## Problem definition

- In this approach, optimization problem is mono-objetive and minimization.
- $R_b$, $L_r$ and $L_e$ are the decision variables.

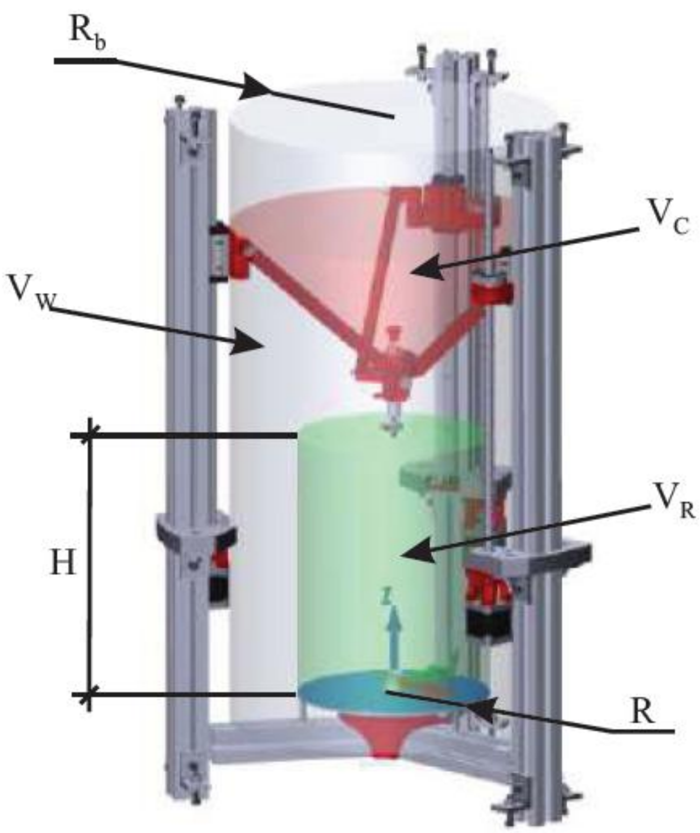


# Activities IDEF0 A1-A2: GA and 3D Model



# Cost function of the otimization problem

$$F_f = \underbrace{\frac{1}{3}\pi R_b^2 \sqrt{L_e^2 - R_b^2}}_{V_c} + \underbrace{\pi H R^2}_{V_w} + \underbrace{\pi L_r R_b^2}_{V_R} + P_s + P_w$$

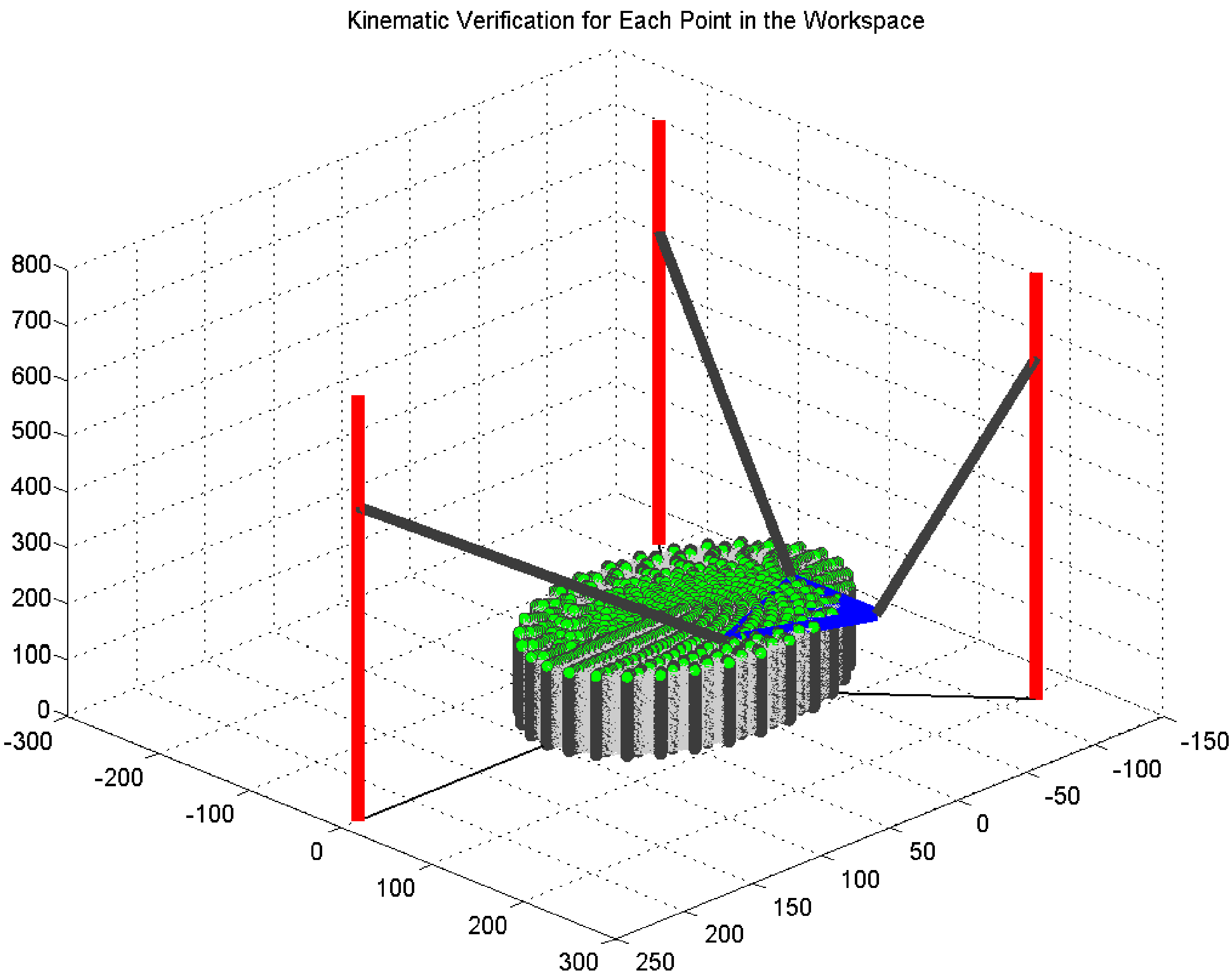



$L_e$: length of each leg
$L_r$: length of the lienar actuators
$R_b$: overall workspace radius
R: usefull workspace radius
H: usefull workspace height

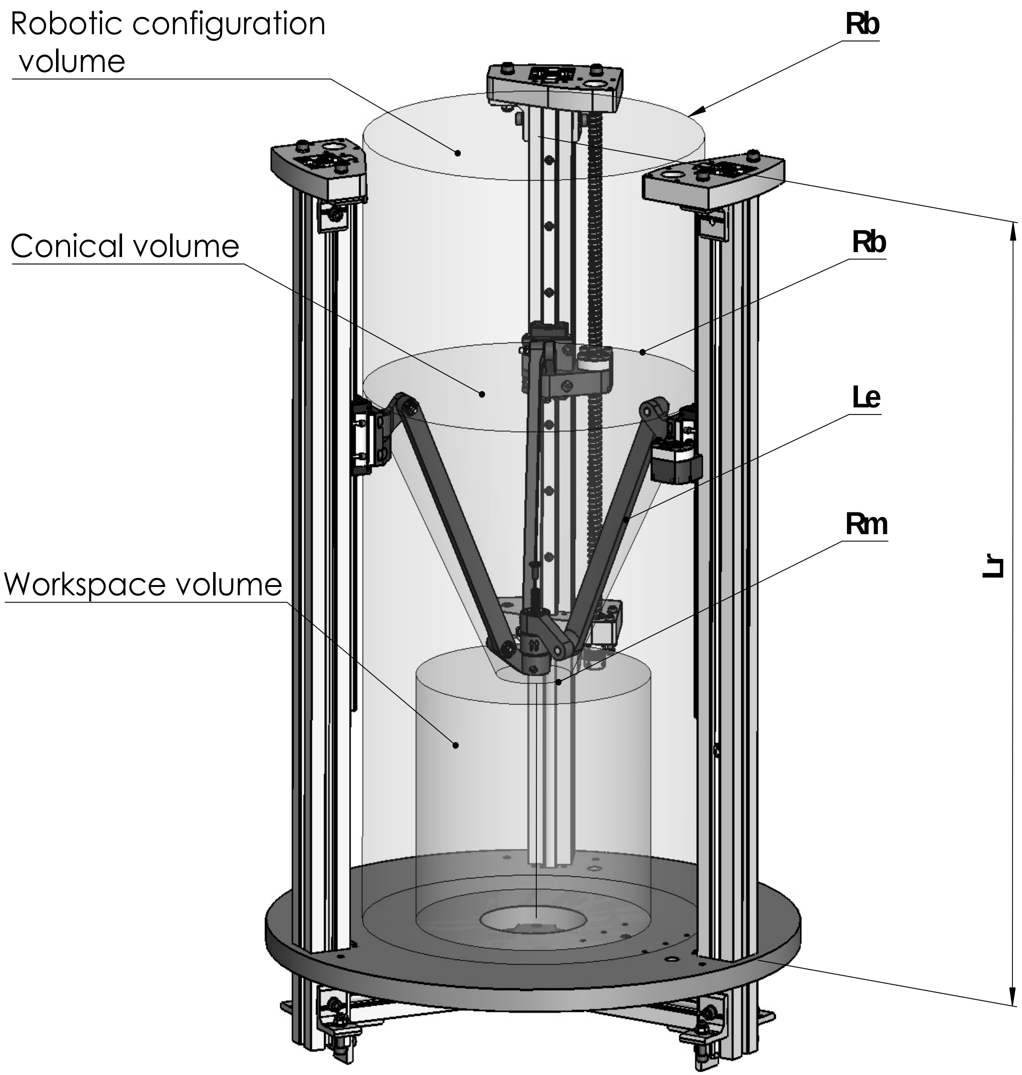
$P_s$: infinite penalty for singularity
$P_w$: infinite penalty for neglect of the workspace

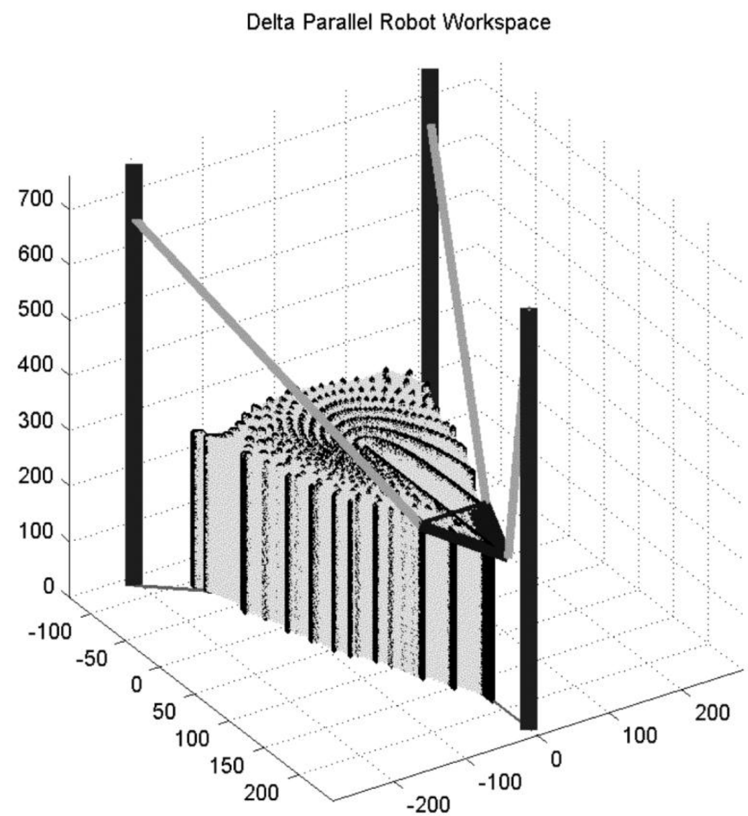
$V_c$: conical bouding-box volume
$V_w$: overall workspace volume
$V_R$: usefull workspace volume

# 3D model linear Delta robot



# Volumes and Workspace



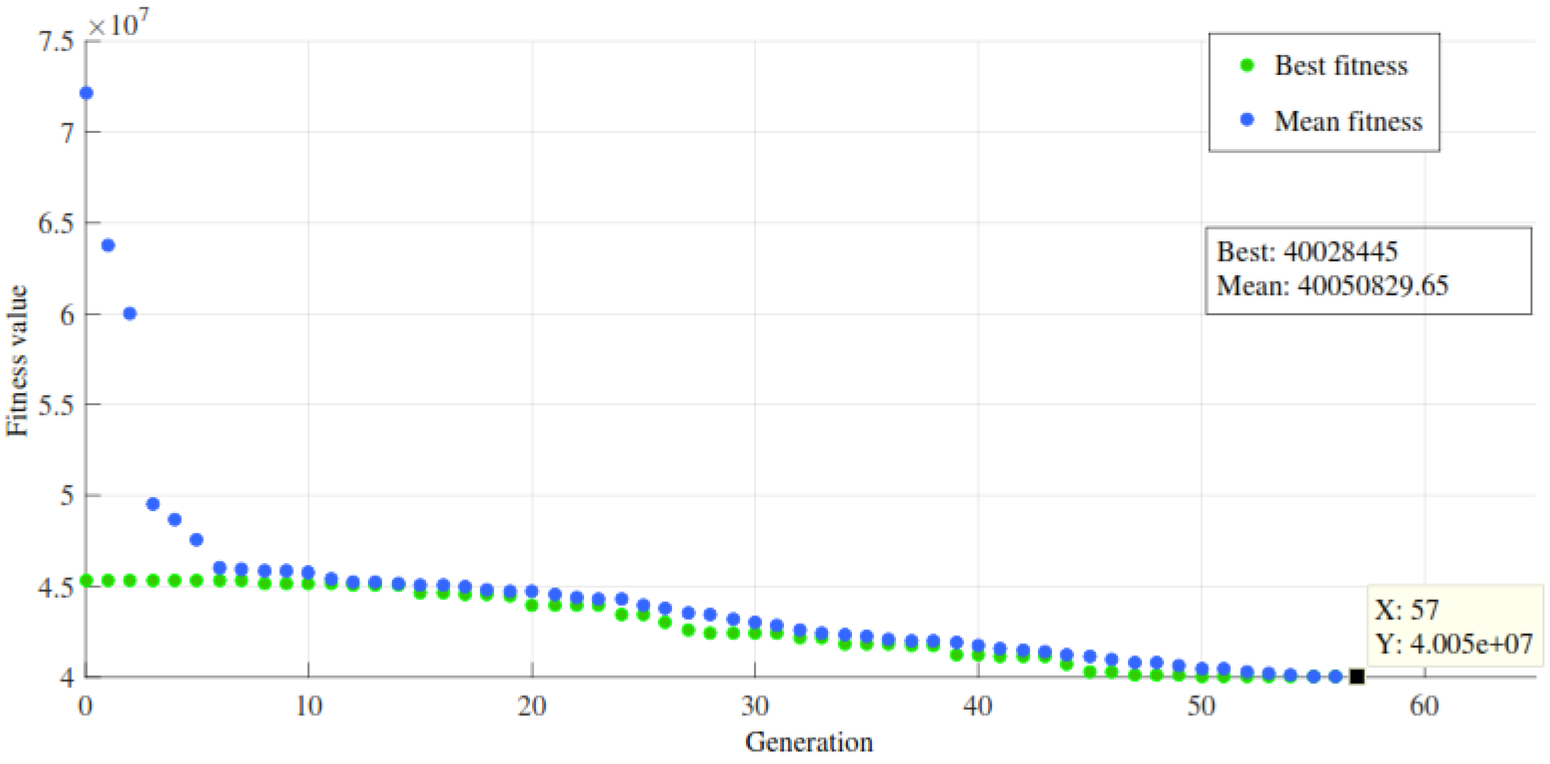



# Conditions for genetic algorithm

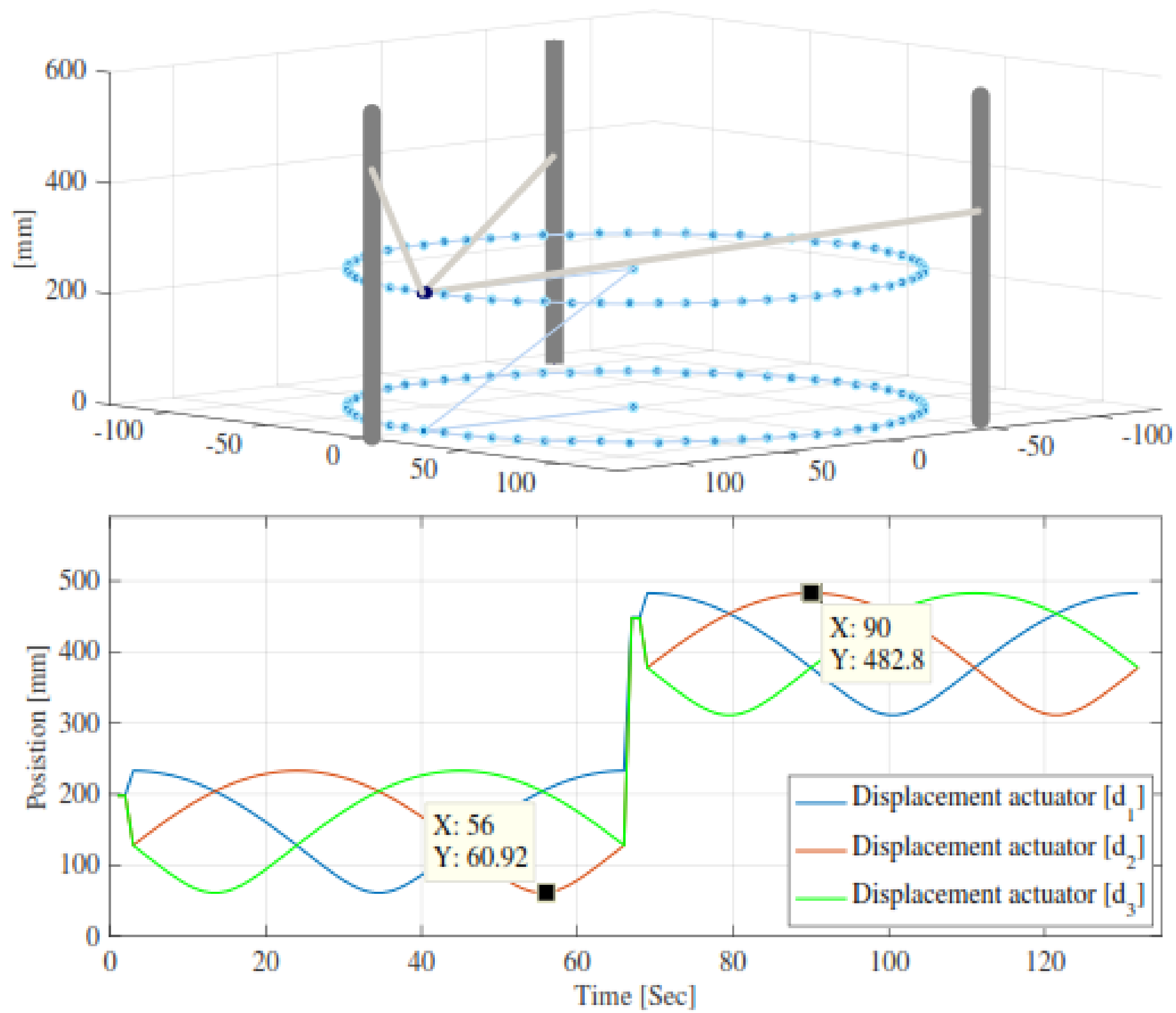
| Lower/upper Bound | $R_b$ (mm) | $L_e$ (mm) | $L_r$ (mm) |
|---|---|---|---|
| $X_{min}$ | R | 10 | H |
| $X_{max}$ | 400 | 400 | 1000 |

| Input Data | Value |
|---|---|
| The Population size | 20 |
| The maximal Generation | 1000 |
| The variable number (Nvars): ($R_b$, $L_e$, $R_m$) | 4 |
| Fitness scaling | Rank |
| Selection function | Stochastic uniform |
| Reproduction (Elite count) | 2 |
| Reproduction (Crossover Fraction) | 0.85 |
| Mutation Function | Adaptive feasible |
| Crossover Heuristic Ratio | 1.2 |
| Migration Forward (Fraction) | 0.2 |
| Migration Forward (Interval) | 20 |
| Stop criteria (Generations) | 100 |
| Stop criteria (Stall Generations) | 50 |
| Cylindrical workspace [Radio, Height](mm) | [100,250] |

# The best score value and mean score

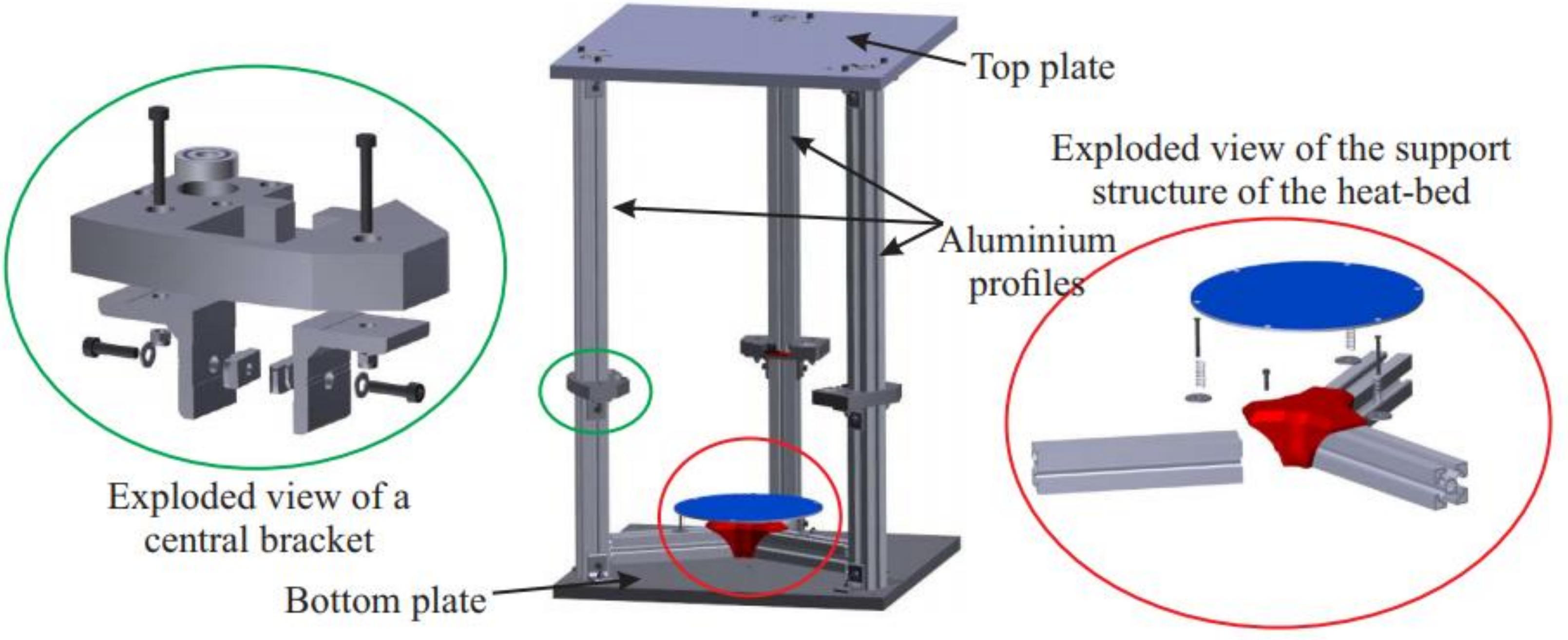


# Results of the dimensional optimization

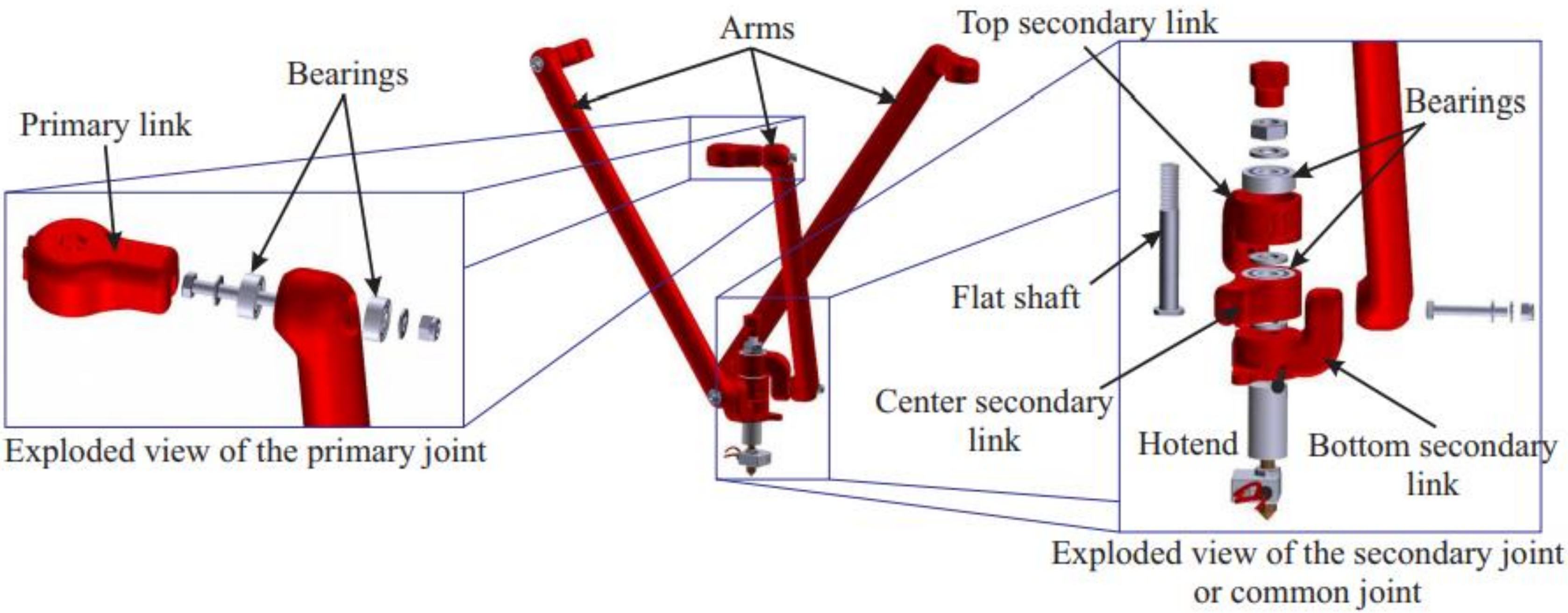



Results: $R_b = 185.4$ mm, $L_e = 283$ mm, e $L_r = 584.8$ mm.

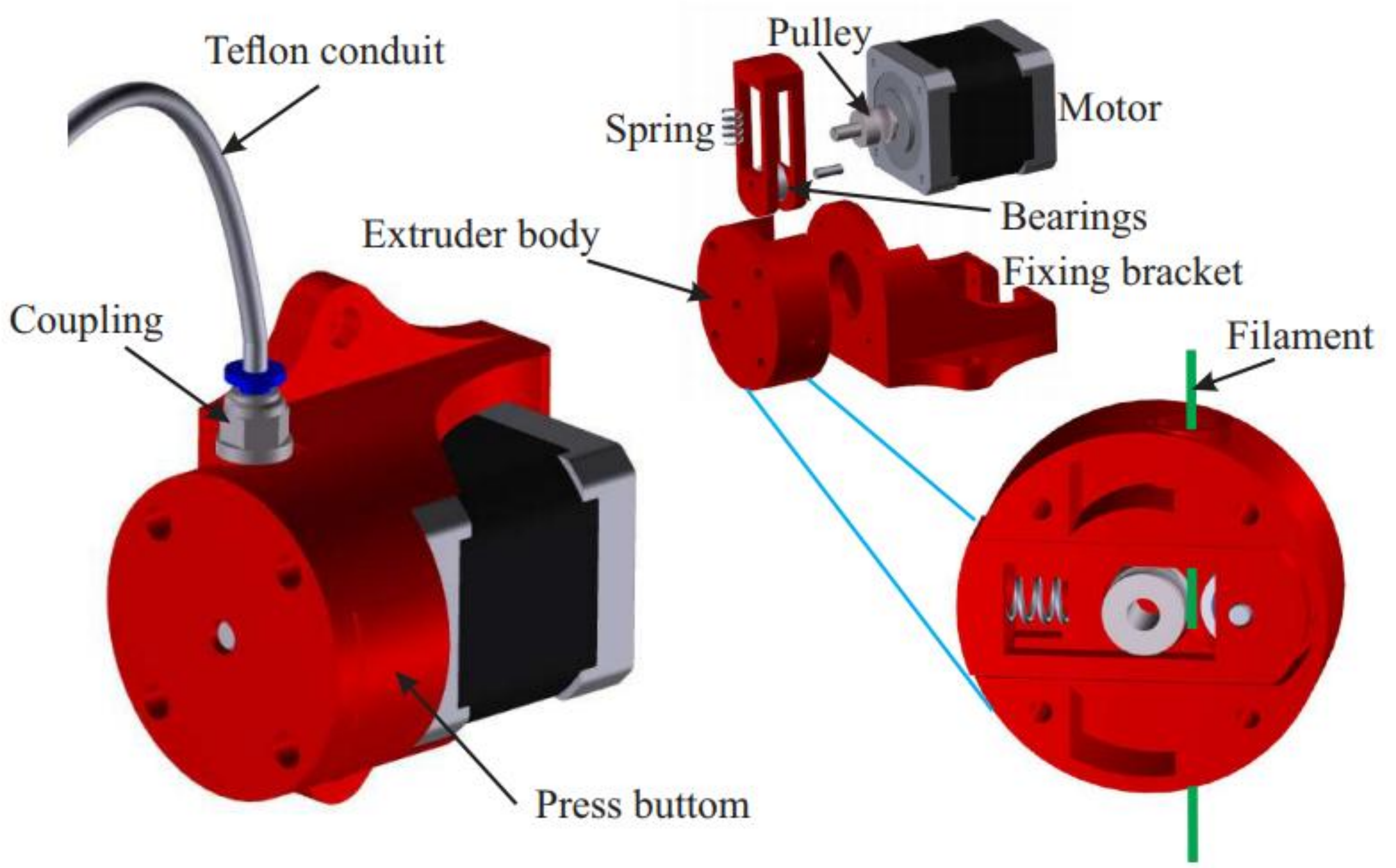
# Detailing of the robot structure



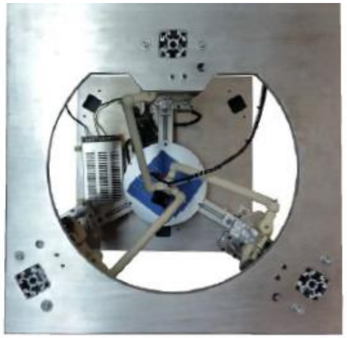
# Detailing of the delta mechanism with single legs

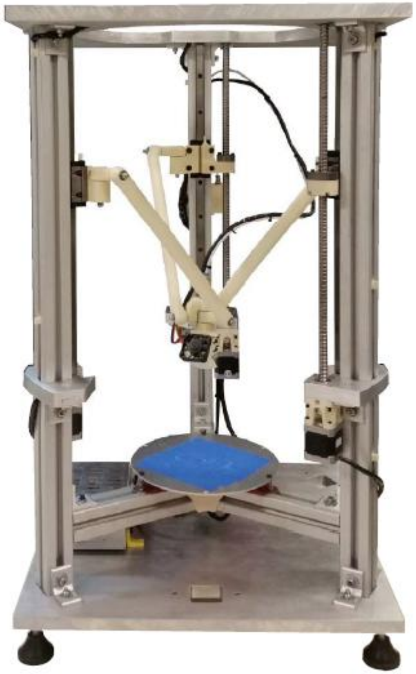


# Detailing of the extruder mechanism

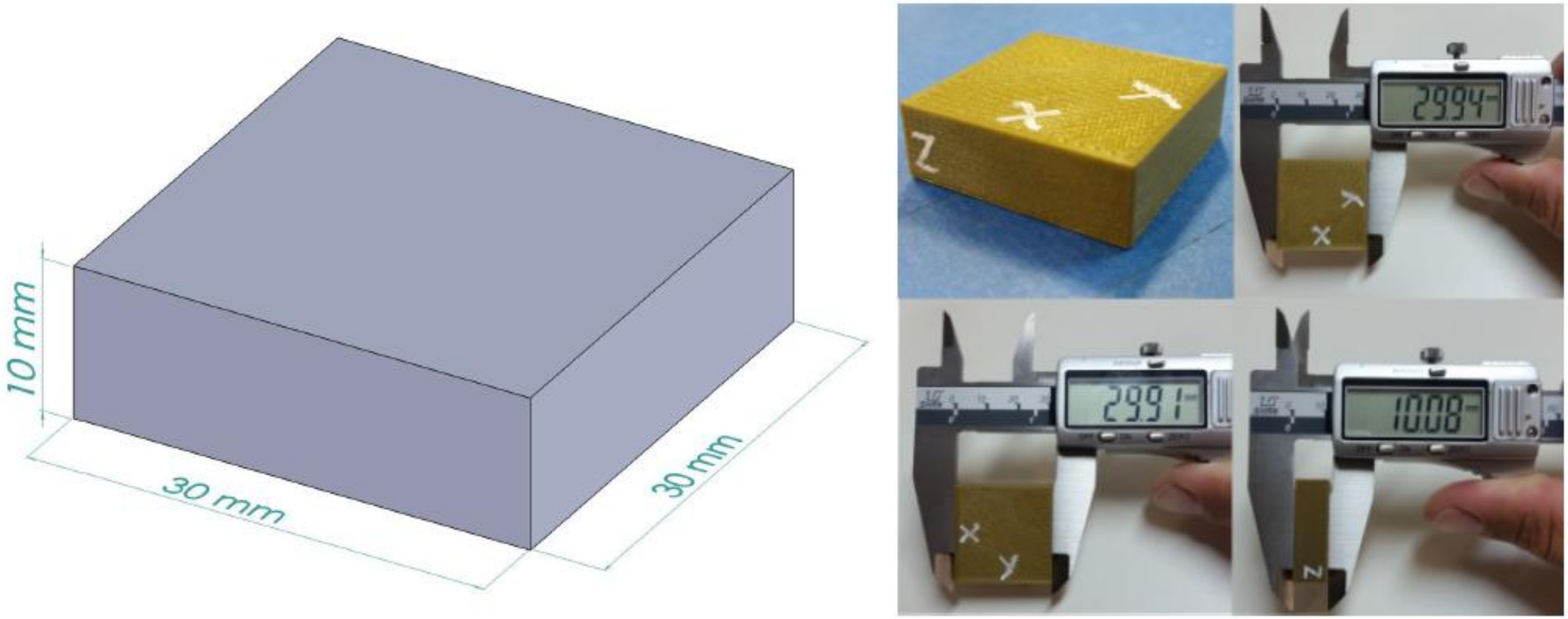


# Prototype of the linear delta robot for AM





# Manufacturing error estimation




Part 1 (Parallelepiped part) - CAD model and printed part

# Manufacturing error estimation

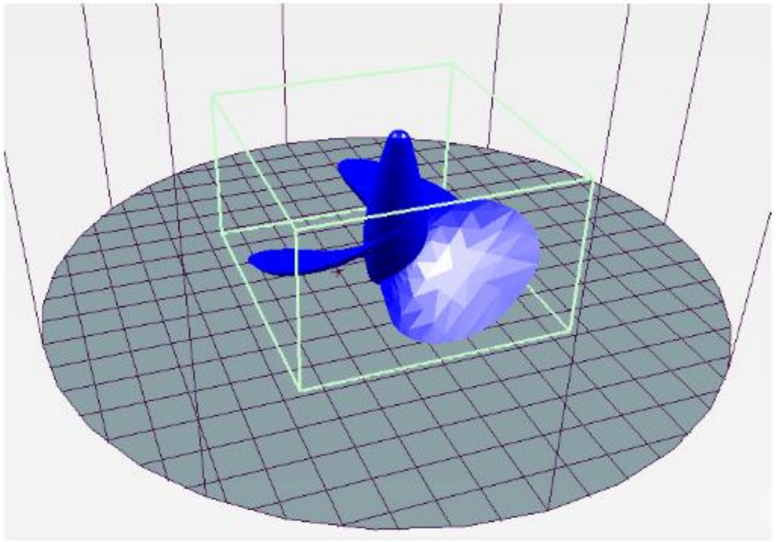
| Measure | X [mm] | Y [mm] | Z [mm] |
|---|---|---|---|
| 1 | 29.91 | 29.94 | 10.08 |
| 2 | 29.90 | 29.91 | 10.12 |
| 3 | 29.95 | 29.91 | 10.12 |
| 4 | 29.94 | 29.95 | 10.07 |
| 5 | 29.91 | 29.94 | 10.07 |
| 6 | 29.94 | 29.94 | 10.06 |
| 7 | 29.94 | 29.90 | 10.05 |
| 8 | 29.94 | 29.91 | 10.05 |
| 9 | 29.95 | 29.90 | 10.12 |
| 10 | 29.95 | 29.91 | 10.10 |
| 11 | 29.94 | 29.92 | 10.08 |
| 12 | 29.94 | 29.91 | 10.08 |

$$\sigma_{xyz} = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2}$$

$$Manufacturing\ Error = 6\sigma_{xyz}$$

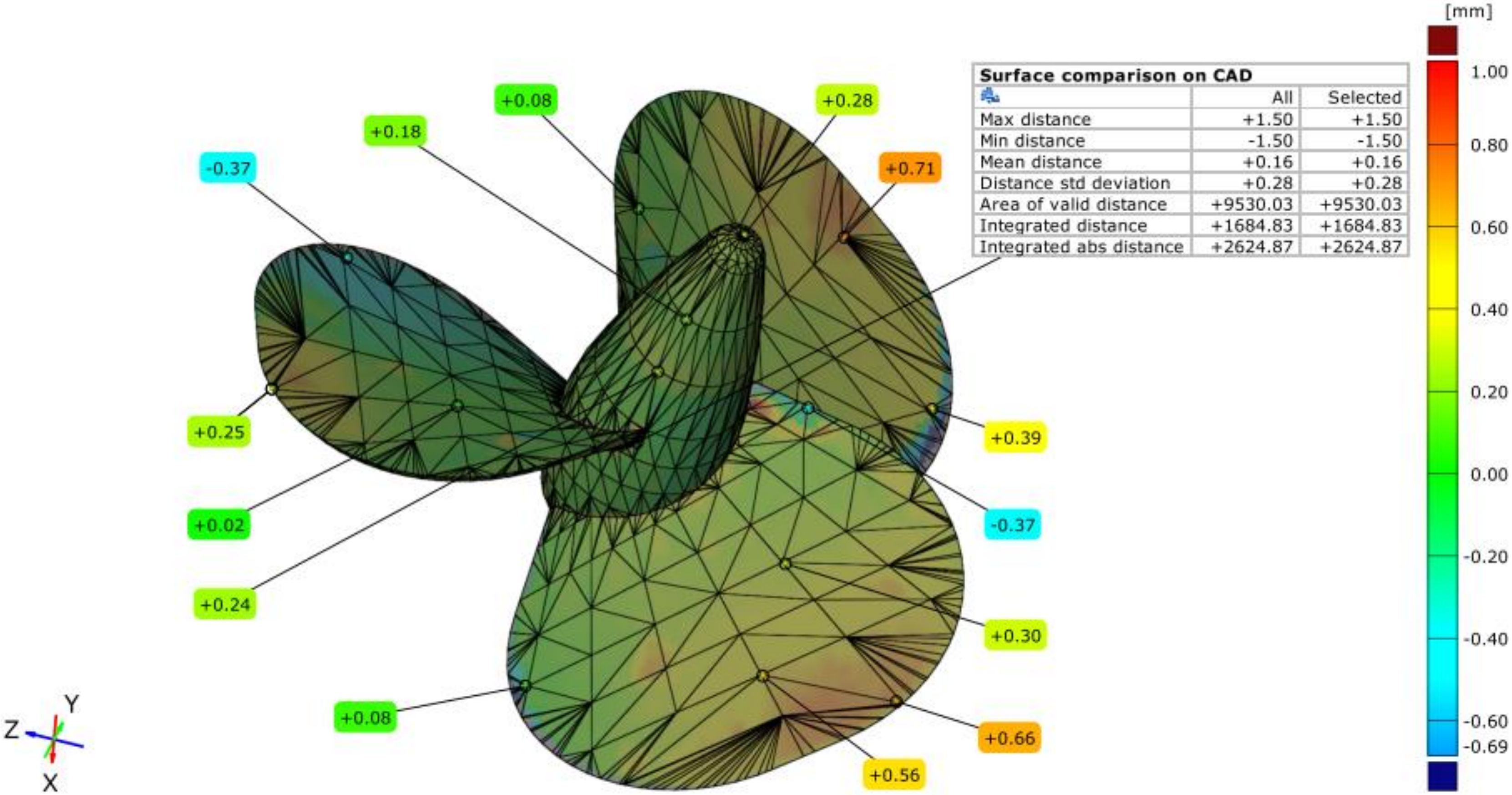
| Confidence Interval (CI) 99.7% | X [mm] | Y [mm] | Z [mm] |
|---|---|---|---|
| Mean | 29.93 | 29.92 | 10.08 |
| Standard Deviation | 0.017 | 0.016 | 0.025 |
| Manufacturing Error | 0.10 | 0.10 | 0.15 |
| Manufacturing Error XYZ | 0.208 mm | | |

# Geometry deviation analysis



Part 2 (Propeller) - CAD model and printed part

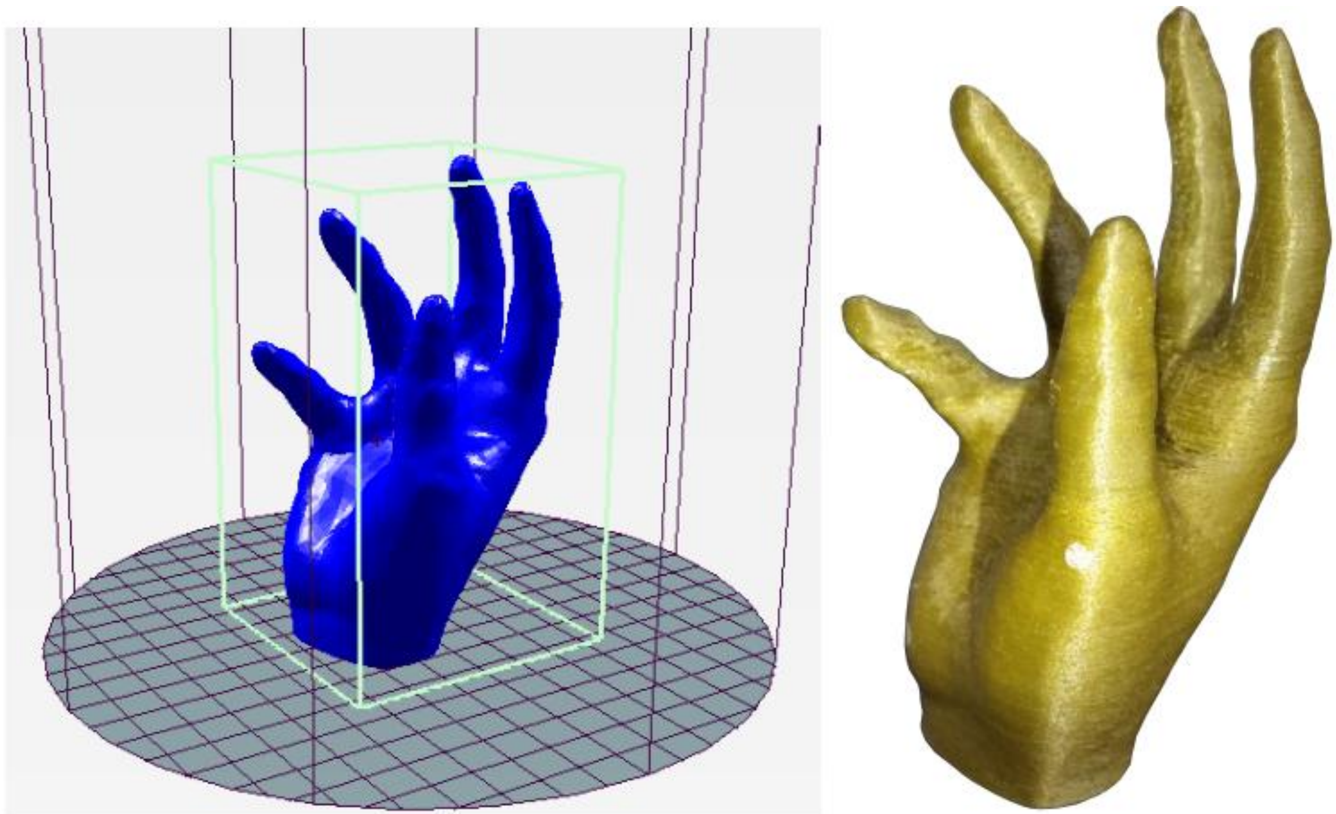
# Geometry deviation analysis




| Surface comparison on CAD | | |
|---|---|---|
| | All | Selected |
| Max distance | +1.50 | +1.50 |
| Min distance | -1.50 | -1.50 |
| Mean distance | +0.16 | +0.16 |
| Distance std deviation | +0.28 | +0.28 |
| Area of valid distance | +9530.03 | +9530.03 |
| Integrated distance | +1684.83 | +1684.83 |
| Integrated abs distance | +2624.87 | +2624.87 |

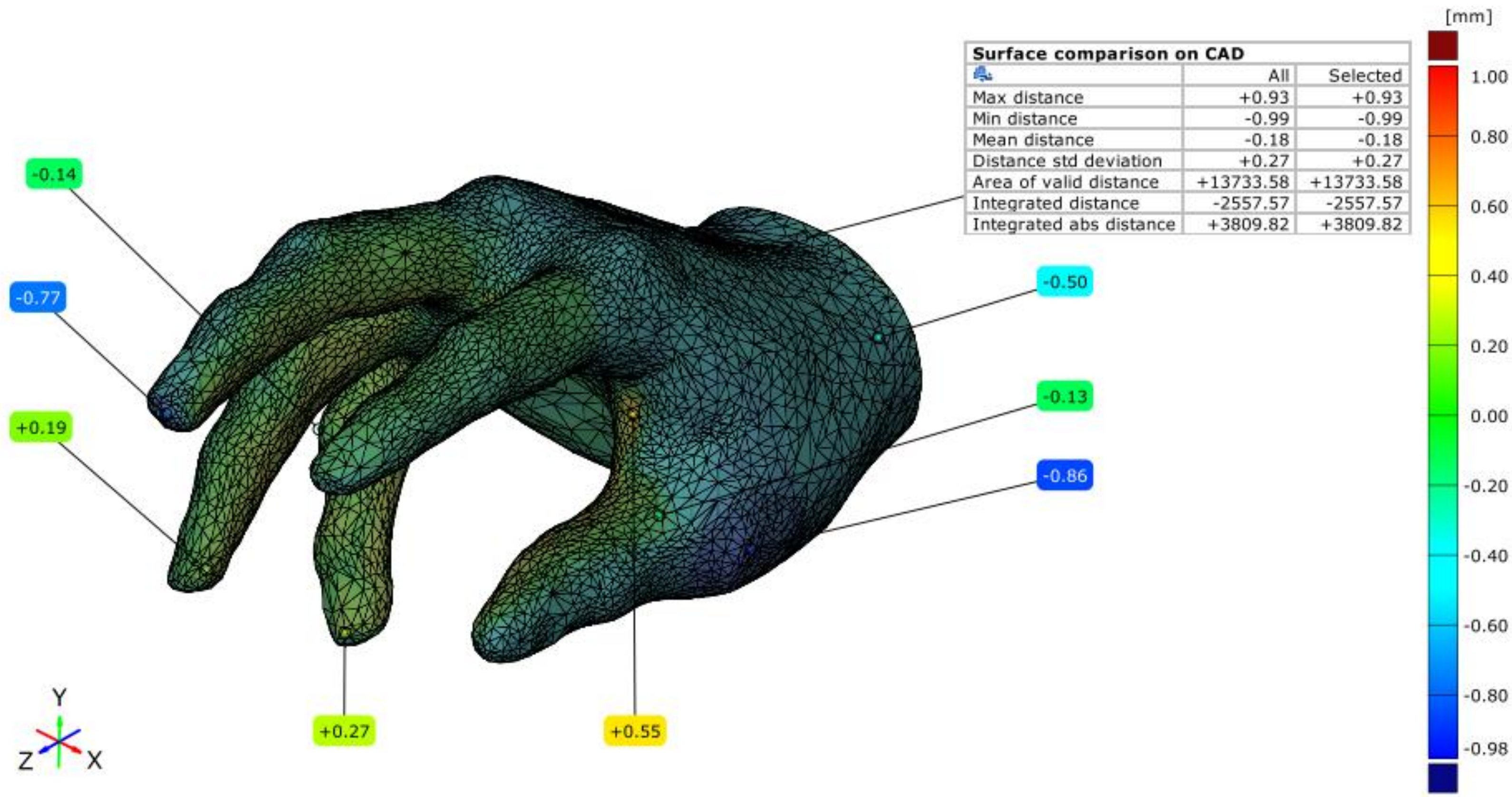
Deviation between the nominal model data and scan model data produced by GOM inspect software for Part 2 - Propeller

# Geometry deviation analysis



Part 3 (Smartphone) - CAD model and printed part

# Geometry deviation analysis




Deviation between the nominal model data and scan model data produced by GOM inspect software for Part 3 – Smartphone Hand

# More printed parts

# Video Demonstration

# Conclusions

- The conceptual design and dimensional optimization of the new structure of linear delta robot for AM was presented.
- The use QFD methodology allowed to gradually systematize the decision-making in the design of the linear delta robot for AM.
- Optimal dimensions of the robot were obtained by implementing a method based on genetic algorithms that yielded satisfactory results.
- A functional prototype was built to validate the design concepts.

Acknowledgements: The authors would like to thank the financial support of the Brazilian government agency MEC/CAPES/CNPq and FAPDF

# Thanks

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