ISTITUTO ITALIANO DI TECNOLOGIA

MECHANISM & BEHAVIOUR CO-OPTIMISATION OF HIGH PERFORMANCE ROBOTS

OBJECTIVES

The objective of this research is to introduce a systematic and scientifically-driven approach to design robots, which can allow robots to utilize today's technology to its maximum potential , and achieve unprecedented performance with less resources. Designing robots is a complex procedure and involves multiple mechanical and electrical parts, each with their own complexity, capabilities and limitations. The complexity of all these components, together with the robot's intended use, make robot design a challenging task.

To address this issue a design optimization approach is proposed that uses realistic mathematical models of the robot's hardware in conjunction with simulations of the tasks that it is required to perform. Then, optimization approaches are used to discover the most physically fit robots based on requirements, available resources, and uncertainties in the real world that affect the final performance.

Requirements and Modelling

- **Realistic models** of the components of the robot
- **Realistic behavior** simulations
- **Limitations** – hardware and behavior (e.g., maximum forces)
- **Co-evolution** of mechanism and behaviors
- **Performance requirements** – what the robot must achieve
- **Decision criteria** – e.g., high performance, energy efficiency etc.

Resources and Uncertainties

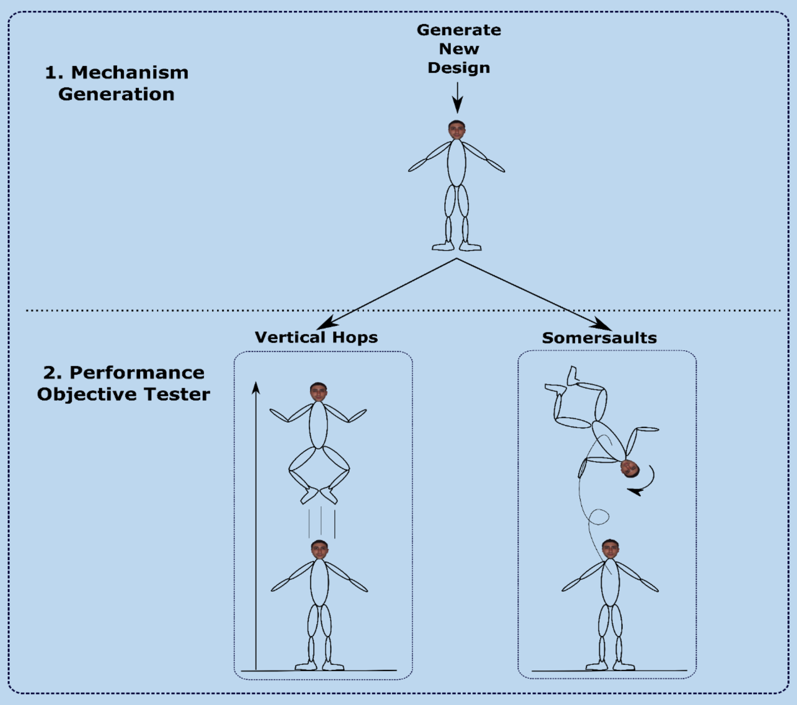
- **Available Resources** – budget, deadlines etc.
- **Optimality** – e.g., is the resulting design the best?
- **Reality** -- imperfections and uncertainties, how is the robot's performance affected by these (e.g., manufacturing errors)?
- **Manufacturability** – can the simulated values be achieved in reality? (e.g., mechanical tolerances)
- **Material properties** – will the robot be able to withstand resulting stresses (FEA)?

Advantages

- **Faster and less expensive** robot production
- Prototype performance **closer to design expectations**
- **Versatile** robots and hence more useful
- **Unprecedented performance**
- **Robust designs and behaviours**

DESIGN APPROACH

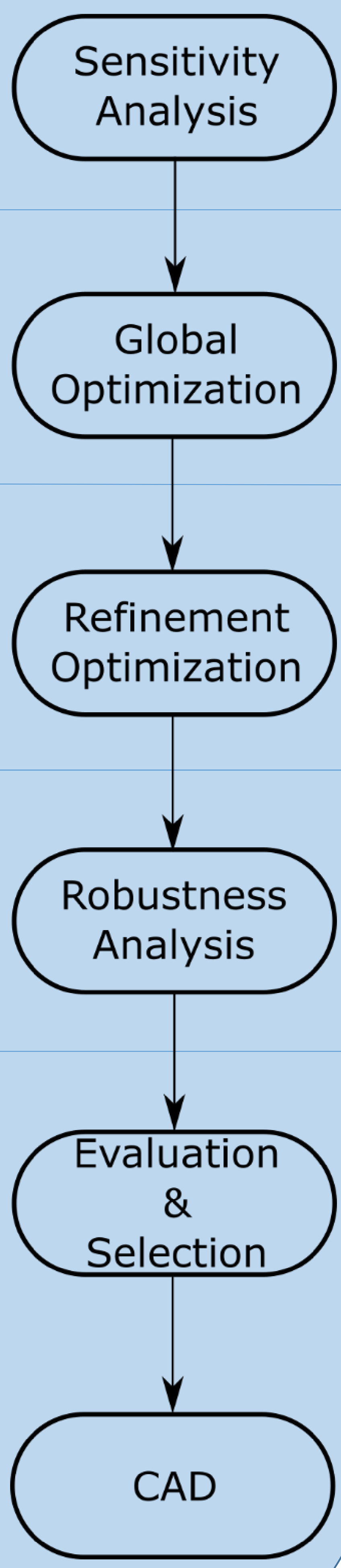
1. OPTIMISATION FRAMEWORK



- **Layer 1**: searches for the fittest design
- **Layer 2**: Performs a series of physical tests to determine the fitness of a given design
- **Co-evolution** of design and behaviors: different designs have different capabilities
- **Versatility**: Multiple objectives
- **Conflicting behaviors**: trade-offs

2. OPTIMIZATION METHODOLOGY

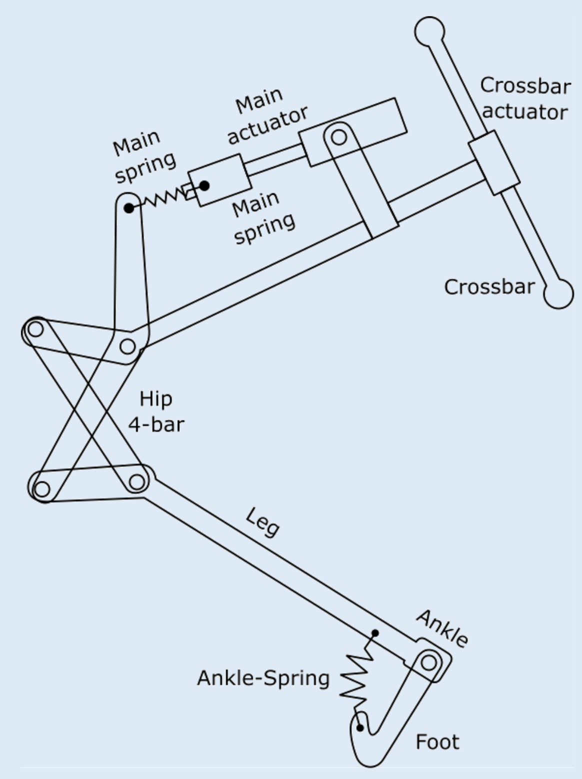
1. **Sensitivity Analysis***:
   - Gaining a deeper understanding of the underlying problem
   - Helps make early design decisions
   - Selecting the most important parameters to optimize
2. **Rough Optimisation***:
   - Find approximate local optima with global search algorithms
   - Pareto front of optimal designs
3. **Refinement of the Pareto Optimal Set**
   - Use local optimisation algorithms for quality improvement
4. **Robustness Analysis* –** the real world is full of imperfections and uncertainties. This step is used for finding the most robust designs in the presence of expected uncertainties in real systems. For each design, a set of new designs is generated based on expected variations of design parameters (e.g., manufacturing errors, initial conditions etc.).
5. **Post-optimisation Analysis**
   - Evaluate results based on a set of desired criteria
   - Optimal trade-off between robustness and performance (or any other criterion) can be used for selecting for the final design to build
6. **Final Design**
   - CAD prototyping
   - Stress analysis (FEA)
   - Information such as maximum forces can be used for FEA or other design decisions such as bearing selection



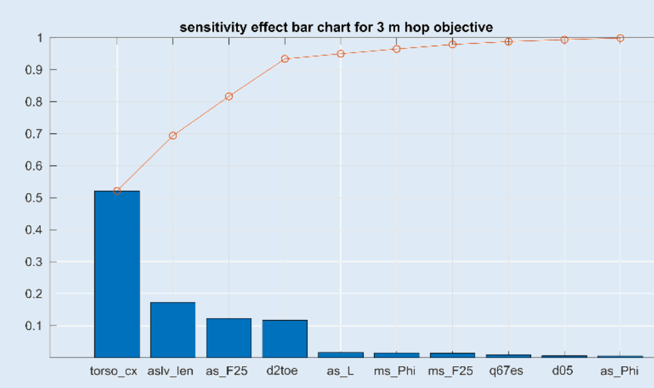
*Design of Experiments (DOE): to generate a set of designs for maximizing the quality of initial information

CASE STUDY

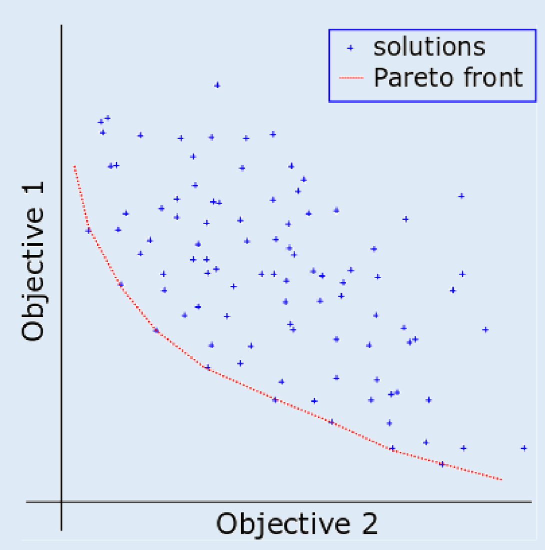
A One-legged Balancing and Hopping Robot



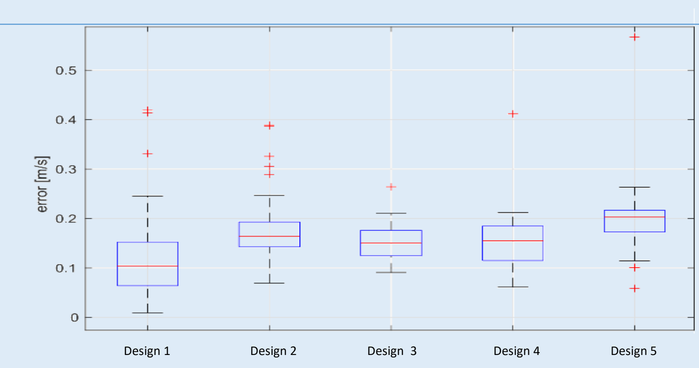
1. **High-performance one legged robot**
   - Balances
   - Hops
2. **Schematic** – early design decisions (e.g., how many motors)
3. **Modeling** – Matlab: **104 parameters**, 14 to optimize
   1. 2 motors
   2. 2 springs etc.
4. **Behavior simulation** – Simulink: **26 parameters**
5. **Performance requirements** – 13 objectives
   - Balancing
   - 3 m vertical hops
   - 2 m triple backflip
   - 9 km/s hopping speed and more.



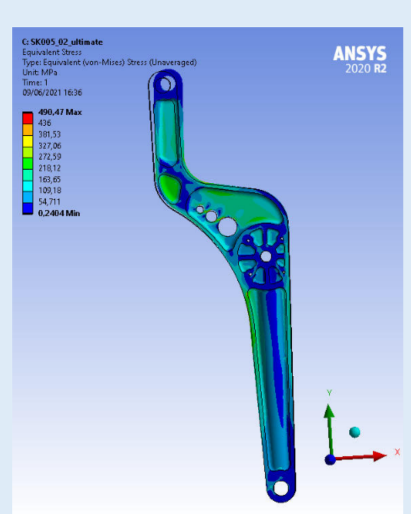
- **Sensitivity-effect – Bar Chart**
  - Contribution of each parameter (bar) to performance
  - Total contribution sums up to 1
  - Parameters with low contribution are not optimized
  - 50% of parameters have a negligible effect
  - Better understanding of the model and less required resources (computational power and time)



- **Pareto Front of Optimal Solutions**
  - Robots need to perform several tasks to be useful
  - Some of these tasks might be of conflicting nature, which creates trade-offs
  - In such cases there are multiple optimal designs
  - The set of the designs with the best trade-off is called the Pareto front.
  - To find this set global optimization algorithms are used.
  - These algorithms have low accuracy, so a refinement is necessary by using local optimization algorithms

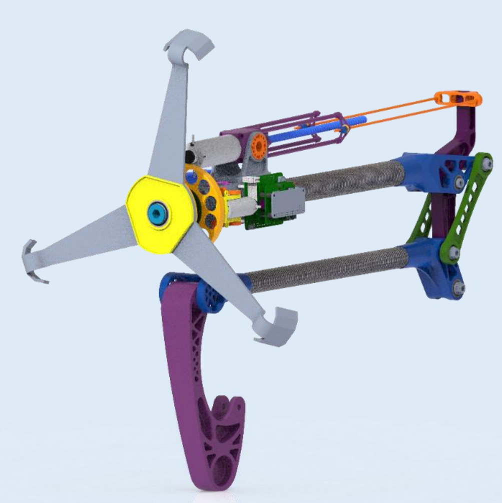


- **Robustness – box-whisker Plot**
  - Performed for each optimal design
  - The robot's performance must be robust against expected imperfections
  - Lower variation (box-whisker) means a more robust design, which is preferable.



FEA analysis **CAD design**

- Simulations provide rough estimations of the conditions that the real robot will be subject to, such as maximum forces.
- For example, parts can be designs and be optimized to withstand maximum forces using FEA
- A final design that can achieve all of the aforementioned objectives has been found and is currently being build (right picture)



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