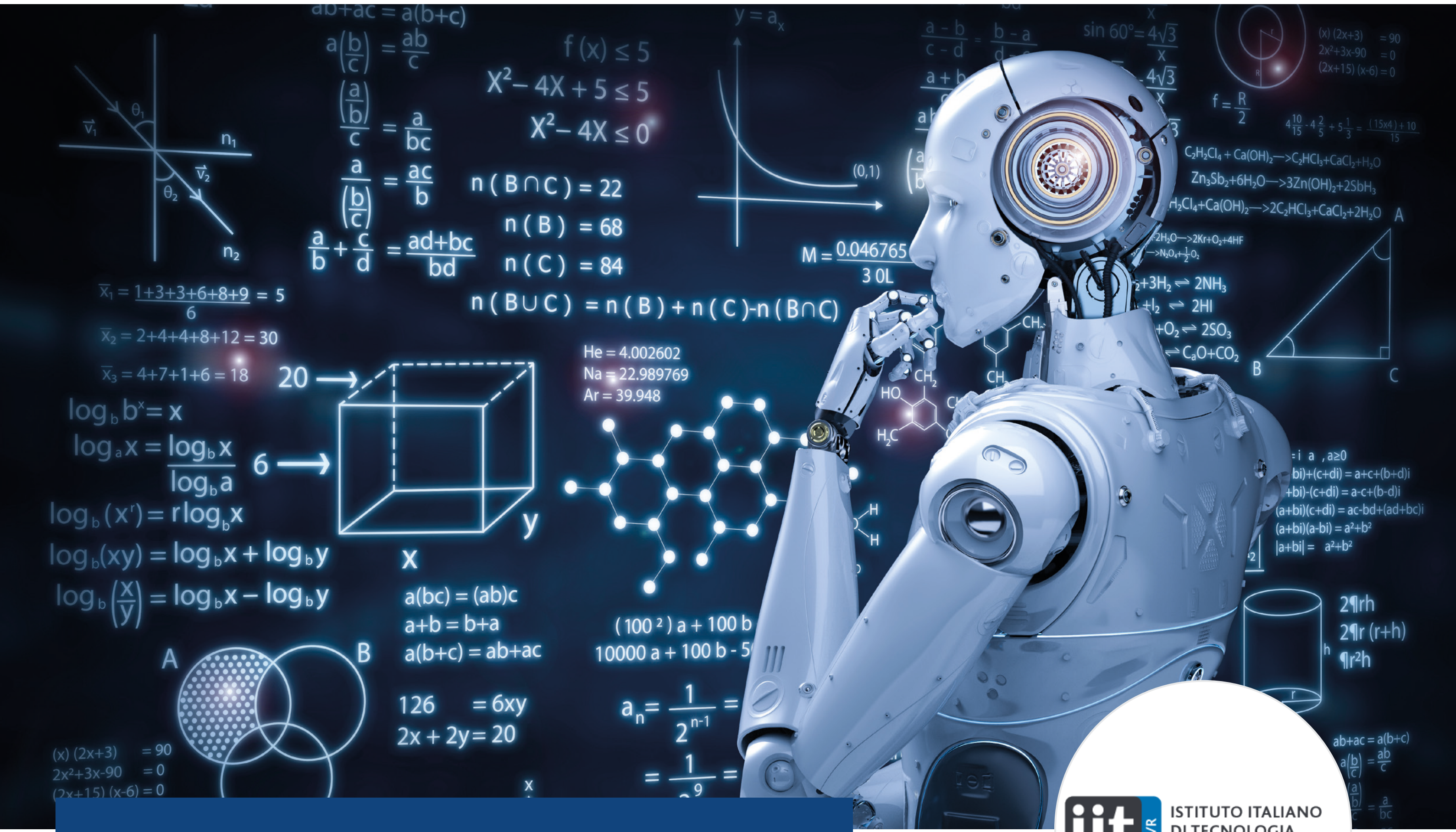

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ADVANCED ROBOTICS

Designing versatile and athletic robots with CAE

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Despite recent technological advances in Artificial Intelligence and engineering, general purpose robots are still not a part of our everyday lives. Robots consist of multiple electrical and mechanical components and must possess great physical ability, versatility, and robustness to substitute or assist humans in either daily or dangerous tasks.

To create and deliver these types of products to market requires realistic models and Computer Aided Engineering (CAE) approaches to guarantee optimal and safe performance with a low production cost. This article presents an example of a proposed design optimization approach with a case study.

Robots are already extensively used in various sectors of industry and have recently found several new applications, for instance in medicine and for inspection scenarios. Today's technology offers light, powerful, and precise actuators, sophisticated sensors, and a variety of materials with amazing mechanical properties. These available technologies mean robots can be made more versatile, faster, and more robust than they currently are. However, the complexity of the individual components, and their limits and capabilities, as well as the intended use for the robot make robot design highly challenging.

It is therefore essential to define systematic and scientifically-based approaches to design, test, and produce robots, similarly to what is done with other high-tech products such as satellites. This article presents a CAE-based design approach that considers the requirements, specifications, available resources, and the constraints in the production line (i.e. manufacturability) together with uncertainties in the real world (e.g. mechanical imperfections). Achieving this requires the creation of realistic computational models and simulations so that CAE techniques can be effectively applied. This can lead to new or improved robots and faster prototyping with fewer design iterations resulting in lower production costs. The proposed approach is applied to the case study of an athletic one-legged robot that can balance and hop, which has been designed to explore the physical performance of today's robotic technology.

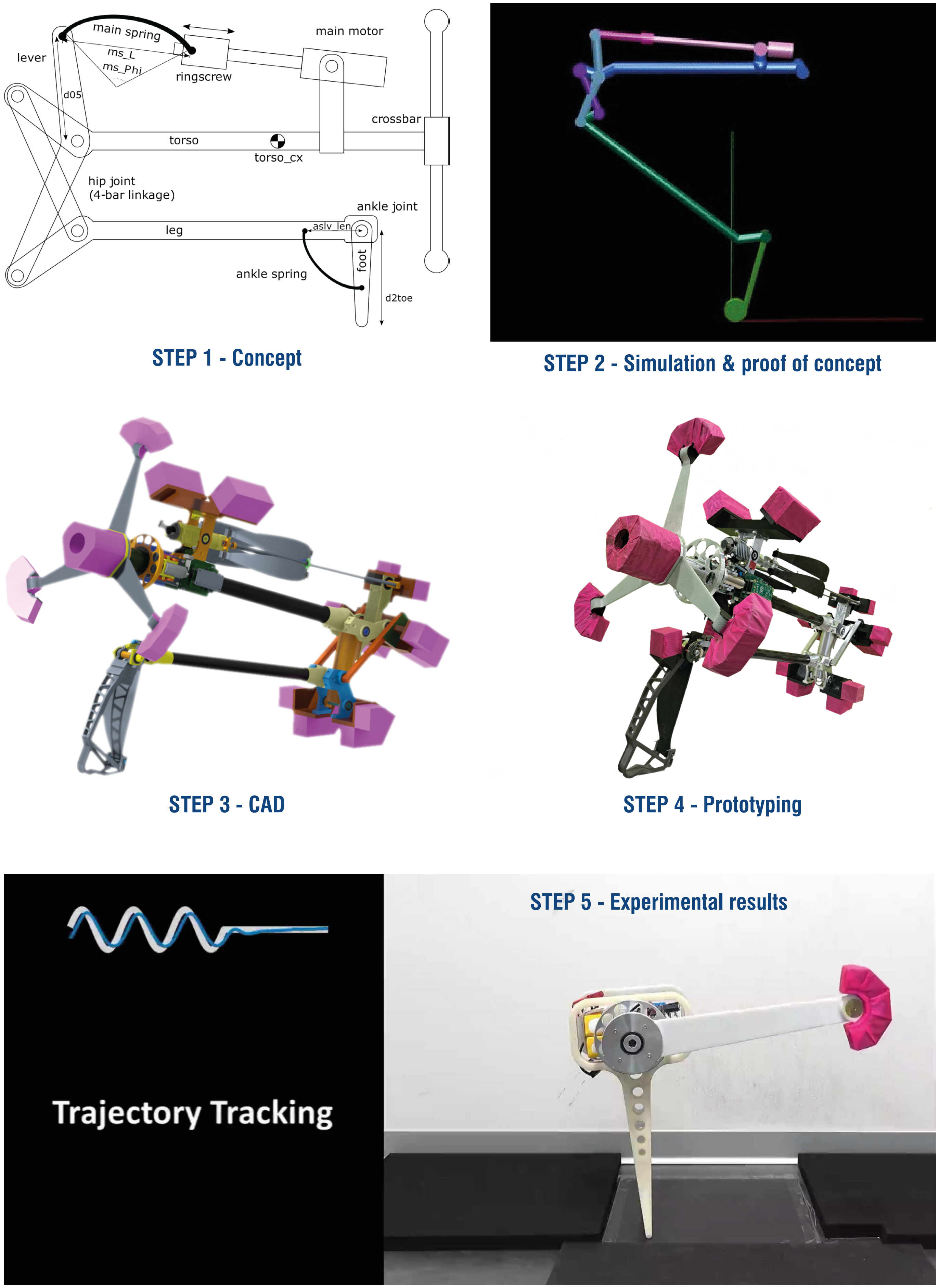

Fig. 1. Overview of robot design process.

The robot design process

Fig. 1 presents an overview of the proposed robot design process, which can be summarized as follows:

- Concept and requirements.
- Specifications, modelling, and simulation.
- Design and behaviour co-optimization (not shown).
- CAD, manufacturing, and assembly.
- Prototyping.
- Experimental results.

Concept and requirements

We now define the overall mechanical structure; actuation, sensing and control technologies; what the robot must be able to do; and how well it should do it.

- The one-legged robot presented in this article was not designed for a specific application but rather to achieve unprecedent performance in a variety of athletic tasks in order to demonstrate the importance of a systematic approach to its design.
- The robot consists of a torso, a leg, a foot, and a crossbar that rotates out of the plane and serves to balance and steer the robot in 3D (see image 1 of Fig. 1). The leg is connected to the torso via a hip joint implemented as a crossed 4-bar linkage. The hip joint is actuated via a linear drive mechanism called a ring screw [1] and a set of fibreglass leaf springs. Finally, the foot is connected to the leg via a spring-loaded ankle joint.
- We wanted to push the mechanism to its limits in order to explore the potential of this approach. We thus decided that the robot should meet the following requirements: a) achieve high vertical hops, b) acrobatics, c) fast travelling hops, d) balancing, and e) surviving a crash-landing undamaged.

Specifications, modelling, and simulation

The simulations serve as a feasibility study with the objective of finding out whether the conceptual design really can achieve all that we want, and how well. The conceptual design can be changed at this or the following stages in response to findings.

The model of the robot was implemented in MATLAB and the simulations were performed in Simulink. This study examines movements in the 2D plane in which only the hip is actuated. The robot and its actions can be accurately described by means of 104 parameters of which:

- 76 are design parameters, and
- 28 are behaviour parameters.

The design parameters provide a description of the complete robot and include information about its mechanism (e.g. kinematics, dynamics); actuators (e.g. electromechanical, and thermal models); sensors (e.g. saturation limits); and more. The behavioural parameters define a virtual environment to simulate all the actions and limitations experienced by the robot during operation. The simulation input is a set of initial conditions and a feed-forward voltage profile to control the brushed DC motor of the hip. After a series of preliminary experiments, we defined the following specifications:

- vertical hops: up to 3m;
- acrobatics: triple backflip;
- travelling: continuous travelling hops at 2.5m per hop; and
- balancing on a very narrow toe at the bottom of the foot

which push the robot to its limits (i.e. the robot reaches current, voltage and/or speed saturation to achieve many of them). To safely reach the maximum physical capabilities of the robot we included individual component limits, such as motor current saturation, speed, and kinematic limits. Then, we mapped the specifications to a multi-objective optimization problem consisting of 13 objectives and 12 behaviour constraints. The objectives are defined as the difference between the desired and the achieved performance, e.g. hop height, and are conflicting in nature, making it a challenging problem.

Design approach

The design approach is divided into two parts: a framework and a methodology. The first is a conceptual structure for the design study, and the second is a series of steps where CAE methods are used to discover optimal outcomes. The following steps are implemented in modeFRONTIER, and a thorough discussion of the approach and the case study is presented in [2].

Optimization framework

Similar to the way a cheetah's body enables it to run at high speeds but is not good for climbing trees, whereas a chimpanzee's body is good for climbing trees but cannot run very fast, this framework was developed based on the premise that a design and its behaviours have an inextricable relationship that can lead to better performance in certain tasks because of physical traits and the behaviours that evolve to exploit them. Fig. 2 presents the two-layer optimization framework. In the first layer a global

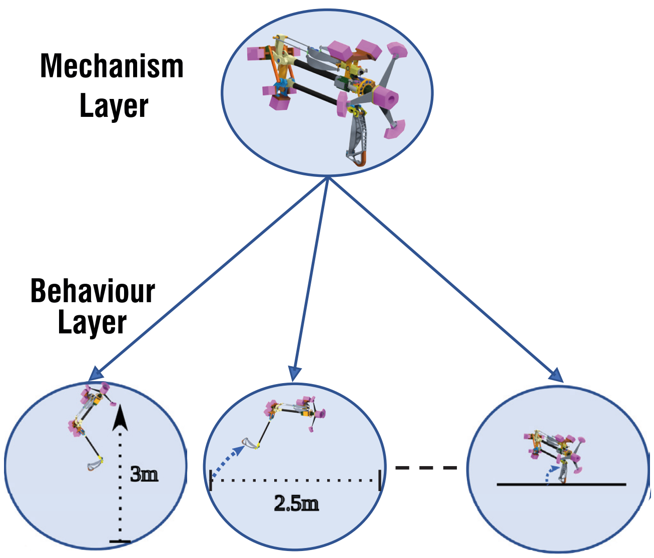

Fig. 2. Design approach, optimization framework.

optimization algorithm (MOGA-II) generates new robot designs by selecting the parametric values for the model. The new design then moves to the second layer where it undergoes a series of physical tests to determine its physical capabilities.

Each test is itself an optimization experiment (MOGA-II) in which optimal behaviours are sought to achieve the best performance. Finally, the best behaviours and associated performance scores (e.g. running speed) are sent back to the first layer to be evaluated and for new designs to be generated.

Optimization methodology

Fig. 3 shows an intuitive representation of the optimization methodology (does not include sensitivity analysis), which consists of five main steps:

- A DOE (Design of Experiments) is performed before each experiment and can lead to faster convergence of the algorithms, requiring fewer computing resources, efficient exploitation of prior knowledge, and a higher probability of finding the best solutions.
- A sensitivity analysis provides a deeper understanding of the problem being investigated to guide early design decisions and select the most important parameters to be optimized. As a result, the computational cost can be reduced and the manufacturing accuracy can be decided based on a component's sensitivity, which can potentially reduce the production cost.
- A rough optimization using global search algorithms generates a Pareto front of designs and their optimal behaviours. Depending on the application or requirements, the designer selects the design with the best trade-offs.
- The Pareto set is refined using local optimization algorithms to improve its quality and achieve maximum theoretical performance.
- A robustness analysis helps unveil the most robust designs given expected uncertainties (manufacturing errors, initial conditions, sensor accuracy and noise, etc.). This can reduce the simulation-to-reality gap and improve the consistency of performance among the same robot designs.

Sensitivity analysis

Thirteen mechanism parameters were selected for this study and tested for their sensitivity in all 13 objectives. The SS-ANOVA approach was used to estimate the interaction effects, and a two-level reduced factorial algorithm was used to generate 1,024 designs.

The parameters selected are spring model parameters, a dynamic parameter, and six kinematic parameters. The outcome is that eight out of 13 parameters have a significant impact on the robot's overall performance across all objectives. The remaining five parameters were set at constant values, which allowed us to proceed with manufacturing and ordering most of the robot components while performing optimization studies.

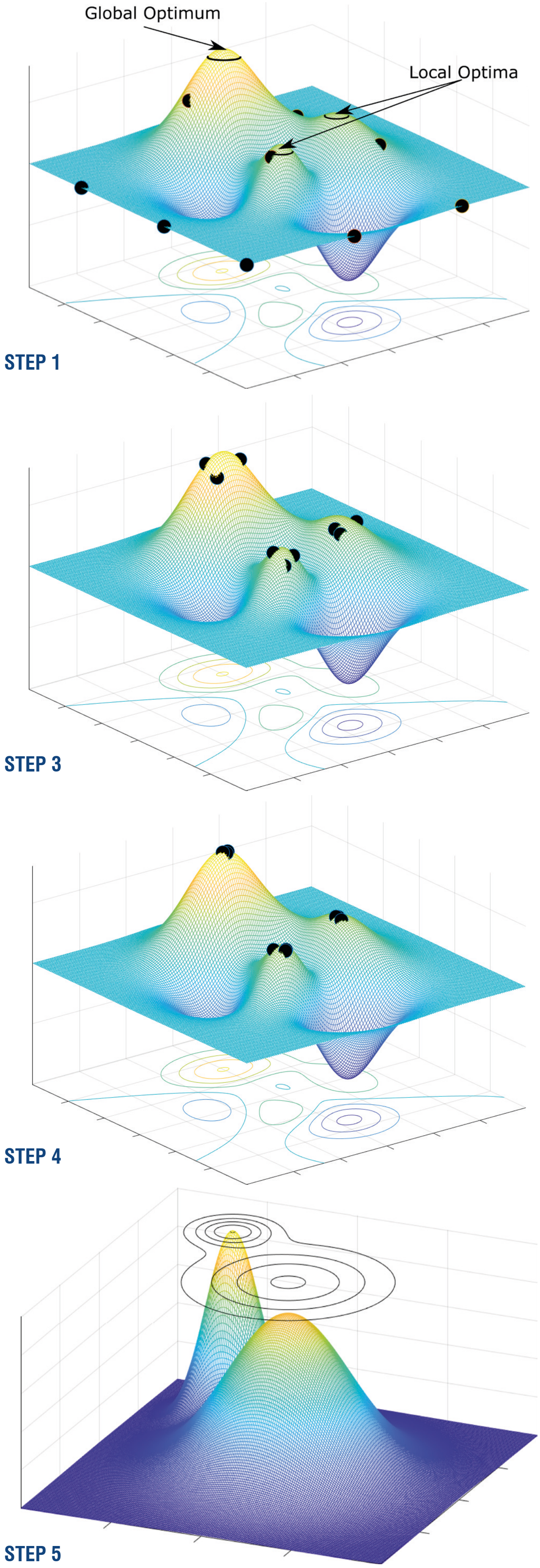

Fig. 3. Design approach, steps 1, 3, 4 and 5 of optimization methodology (sensitivity analysis is not shown).

Rough optimization

In this part, hundreds of designs were generated in the first layer and tested in the second layer. Among the resulting 34 designs that met the performance requirements and did not violate any constraints, we selected five Pareto optimal designs, which were the best: a) vertical hopper, b) acrobat, c) runner, d) balancer, and e) the design with the best overall performance.

To give an idea of the trade-off between the performance of these designs, the best running design expends 11% less energy (drawn from the battery) on running at the same speed as the design with the best overall performance; however, it underperforms in balancing and acrobatics. These results are discussed extensively in [2].

In another study with the same approach, we discovered skilled one-legged runners that can achieve running speeds of up to 22km/h; however, they had very poor performance in the other tasks.

Refinement optimization

An additional round of optimization was then performed to discover the maximum theoretical performance of the designs. The result was increased performance in most objectives. For example, the best runner increased its maximum hop height by 5%.

Robustness analysis

In this study, we examine the robustness of the designs discovered for the 13 objectives with respect to expected variations in 15 design parameters. Using modeFRONTIER's robust design optimization tool we generated 50 new designs for each design in the Pareto front. We did this using multimodal distributions to model the uncertainty and then sample them. For instance, fibreglass springs were measured to have a difference in their maximum stiffness of up to 3% when tested on a tensile strength machine.

The results showed that even for slight variations in the robot mechanism, significant discrepancies can be observed between the best and average performance.

For example, the best acrobat, which has a maximum hop height of 3m, was found to have an average performance of 2.8m, which is 7% lower than expected. The results indicate that this method can help bridge the gap between simulation and reality, justify inconsistencies in performance, and can be used as an additional evaluation criterion for design selection [4].

Experimental results and prototyping

Physical prototypes must be built and tested because no simulation or mathematical model can capture every detail of physical reality, so prototypes are needed to serve as "ground truth".

The first complete prototype is presented in image 4 in Fig. 1. It has a length of 1.4m with the hip fully extended and has a mass of ~5.3kg. Image 5 also shows a frame from the experimental results for balancing for the first incomplete version, published in [3].

Conclusion

The results of this case study show that versatile robotic systems can be governed by complex trade-offs, which may depend on many factors including the system components, their combined behaviours and limitations, and the tasks for which they are designed.

Moreover, in complex and highly dynamic electromechanical systems, typical optimization approaches tend to over-optimize the model, which results in theoretical performance that is unfeasible in practice. In conclusion, building robots that are efficient physical actors is not an easy task, and designing them for widespread commercial use renders imperative the need for more systematic and scientifically grounded approaches during their design process.

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