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Design of a Modular Gripper Family Using Solution Spaces

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Abstract— Robotic grippers are often designed as custom solutions to meet specific handling requirements, resulting in a large number of component variants and high lifecycle costs. Optimizing grippers for individual use cases will maximize performance. When they share components, cost may be reduced, however, performance may be compromised. This work aims at minimizing the number of components while maintaining a minimum performance. Co-designing grippers that share components across multiple use cases is an expensive combinatorial optimization problem. Unlike conventional optimisation approaches that yield point-based solutions, the proposed method here identifies the intersection of permissible design variables—so-called solution spaces—to define a compact, standardised set of interchangeable modules. This way, gripper families can be identified at significantly reduced numerical cost. The approach is applied to grippers intended for 6 different cylindrical objects of varying mass, geometry, stiffness and friction coefficient. The number of component variants could be reduced from 21 for individual grippers to 9 for the resulting gripper family.

Index Terms— Modular design, modular product family, solution spaces, robotic manipulation, design automation, product architecture, platform strategy.

I. Introduction

The demand for adaptable, cost-efficient robotic systems is growing with the rise of collaborative and service robots, shorter product life cycles, and increasingly diverse tasks [1], [2]. Conventional grippers are often optimized for narrow use cases, resulting in high variant counts, limited reuse, and elevated lifecycle costs—hindering seamless system integration [3], [4]. Modular product families address this by enabling multiple configurations from a reduced set of standardized components. However, determining the optimal modularization is challenging: over-standardization can compromise performance, while excessive customization erodes reuse benefits. In integrated robotic systems, the gripper must also align mechanically and functionally with other subsystems, amplifying these trade-offs [5], [6], [7]. This paper applies Solution Space Engineering (SSE) [8], [9] to the design of a modular, three-finger electromechanical gripper for cylindrical objects of varying mass, size, and mechanical properties like stiffness or friction coefficient.

II. State of the art

A. Gripper design in robotics

Grippers are essential components in robotic systems, enabling secure and precise manipulation of objects. The VDI 2860 guideline defines grippers as subsystems that create contact, grasp, and reposition objects while ensuring positional stability during the entire manipulation process [10]. They are categorized by their actuation and working principles, including mechanical, pneumatic, magnetic, and adhesive designs [3]. Mechanical grippers dominate industrial usage due to their robustness and adaptability, typically using form or press-fit closures and driven by electric or pneumatic actuators. Three-finger centric grippers offer high precision for cylindrical objects and are advantageous for symmetrical load distribution [3], [11]. Pneumatic systems, while mature and cost-effective, have high energy demands and lower adaptability, whereas electromechanical systems enable programmable motion and energy efficiency, which are critical in collaborative robot (cobot) applications [11], [4]. Market surveys reveal a lack of cost and weight optimization in standard portfolios, and custom grippers often result in overdimensioned solutions with limited reuse across applications [4], [12]. To address these issues, recent academic developments emphasize low-cost, lightweight gripper concepts using rapid prototyping and modular architectures [1].

B. Product family design

As product variety increases due to global competition and individualized customer demands, modular product families have become a way to manage internal complexity. A product family is defined as a collection of variants sharing functional principles, components, or production processes [5], [13]. Internal complexity arises when market-driven external variety is translated directly into unique internal structures, leading to inefficiencies across development, logistics, and service [5]. Modular design aims to decouple external variety from internal complexity. This is achieved through strategies such as [5], [13]:

- Common module strategy (Gleichmodulstrategie): shared modules across product families,
- Scaling strategy (Baureihenstrategie): scalable variants from a core product,
- Modular kit strategy (Modulbaukastenstrategie): combinable standardized modules,
- Platform Strategy (Plattformstrategie): core systems shared across multiple configurations.

Each strategy supports different business goals, from economies of scale to responsiveness and market differentiation. Identifying the optimal level of standardization

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is a design challenge and is crucial for balancing complexity, cost, and functionality [6], [7]. Ponn et al. [15] emphasize that design decisions in early development stages lock in a majority of lifecycle costs, making strategic modularization critical. Eilmus [6] and Rötzer [7] highlight that poor modular planning may increase cost through overdesign or underutilized reuse potential.

C. Solution space engineering

To manage the complexity of designing modular product families, SSE provides a model-based, quantitative approach. SSE was introduced by Zimmermann et al. [8] to formalize the exploration of valid design configurations by simultaneously evaluating all relevant constraints and performance requirements. The SSE process consists of three main steps [8]:

1) Framing: Define design parameters (DP) and design variables (DV), and quantities of interest (QoIs) such as gripping safety or structural limits.
2) Evaluation: Establish bottom-up mappings that map DV values onto QoIs, e.g., using simulation models or formulae or surrogate models.
3) Design: Derive solutions or sets of solutions, here box-shaped solution spaces, on which all designs satisfy all system level requirements.

Bottom-up mappings predict object falling, object deformation, structural integrity, and diameter compatibility for various object types. From these mappings, solution spaces are calculated and boxes of good designs identified. Whenever there is an overlap of solution boxes for two or more grippers, commonalities are identified, enabling the design of a modular product family with common components.In this work commonalities are found by visual inspection of overlapping solution spaces. In more complex works, automated methods such as clustering algorithms could be applied to identify optimal modular architectures [9], [16], [17]. Moreover, the procedure is proven to work with more complex models [9] as well as more DPs, DVs and QoIs [18], [19].

III. Methodology

This section outlines the detailed methodology applied to design a modular robotic gripper family.

A. Definition of requirements

A use-case-driven requirement analysis was performed based on real-world objects typically encountered in service robotics applications. The following objects to be gripped were identified (see Fig. 1): coffee mug, beverage can, paper towel roll, salt dispenser, juice glass, paper cup. Requirements were derived via user stories, capturing handling safety, precision, and object variability.

Fig. 1. Use cases for gripper design

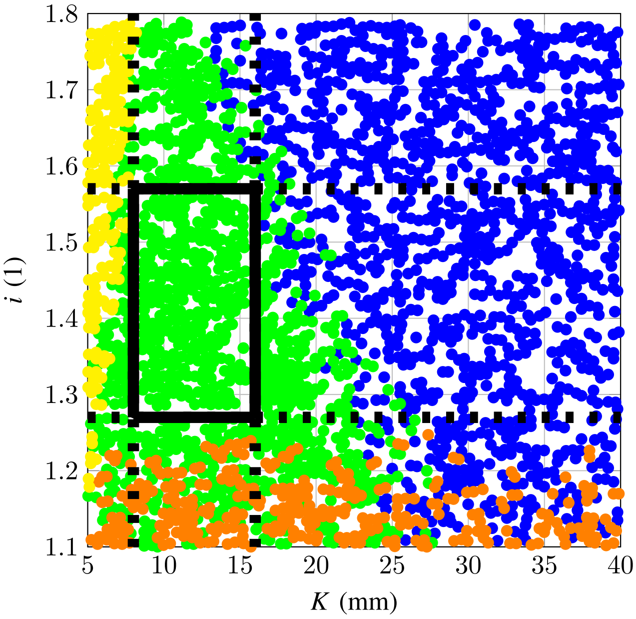

Fig. 2. Modules of the gripper

B. Definition of gripper architecture

The gripper was divided into functionally distinct subsystems, allowing for targeted modularization (Fig. 2):

- Actuation Module: Servo motor and drive train,
- Transmission Module: Planetary gear enabling synchronous motion,
- Finger Module: Interchangeable gripping fingers with contact pads,
- Interface Module: Quick-change coupling to the robot arm.

Each module was designed to be independently scalable, forming the basis of a scalable product architecture [5].

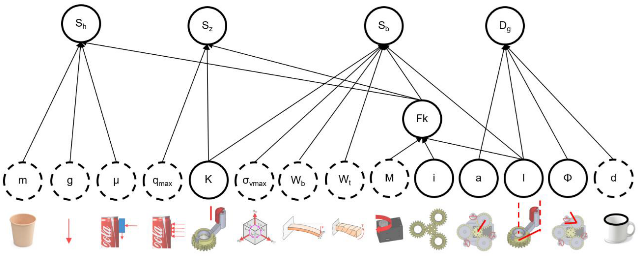

Fig. 3. Attribute Dependency Graph linking design variables and quantities of interest. Below the ADG pictures of the physical meaning of each DV and DP can be found.

C. Quantities of interest and design variables

To ensure that all gripper variants fulfill safety factor and typical performance requirements [4], [20], four quantities of interest (QoI) were defined:

- S_h: Safety against object falling (grip force vs. weight) with associated requirement $S_h \geq 3$,
- S_z: Safety against object deformation (contact pressure limits) with associated requirement $S_z \geq 1.5$,
- S_b: Safety against structural failure (stress in finger material) with associated requirement $S_b \geq 1.5$,
- D_g: Gripping diameter ratio (compatibility across object sizes) with associated requirement $D_g \leq 1$.

The dependencies between design variables and QoIs are visualized in an Attribute Dependency Graph (ADG), shown in Fig. 3. It captures the causal links between design variables, physical effects, and performance outcomes.

D. Establishing bottom-up mappings

A bottom-up analytical model was created to map DVs onto QoIs, enabling numerical evaluation of each design. Key DVs are:

- l: Finger longitudinal length,
- i: Gear transmission ratio,
- K: Contact surface length,
- a: Finger axis spacing.

The relationships are provided as formulae; see Table I.

S_h is computed as $\frac{F_a}{F_n}$ with F_a as the applied force and F_n as the necessary force to hold the object. The applied force is defined from the motor torque, the gear ratio as well as the length of a finger as $F_a = \frac{M \cdot i}{l}$ while the necessary force is computed from the mass of the object to be held m, the gravitational acceleration g and the friction coefficient $F_n = \frac{m \cdot g}{\mu}$. The result is $S_h = \frac{M \cdot i \cdot \mu}{m \cdot g \cdot l}$.

The contact force is calculated from the drive torque M, the gear ratio i, the finger longitudinal length l, and the number of fingers (three) $F_K = \frac{M \cdot i}{3 \cdot l}$. The contact force is distributed over the contact length K of the contact pad and produces an actual line load q_{ist}. This is compared with the maximum permissible line load of a gripped object or the permissible line load of the contact pad q_{max}. The maximum permissible line load is either that of the gripped object, or 5 N/mm if the object is non-deformable. (A higher line load would damage the contact pad). This value corresponds to the maximum at which the contact pad is not yet fully deformed $q_{ist} = \frac{F_K}{K}$. The safety factor against crushing is then $S_Z = \frac{q_{max}}{q_{ist}}$.

The safety factor against fracture at the critical cross-section is defined as $S_b = \frac{\sigma_v}{\sigma_{va}}$. The bending stress is calculated from the contact force F_K, the bending section modulus W_B, the torsional section modulus W_T, and the permissible equivalent stress σ_v in a finger. The critical cross-section is located at the transition between the finger and the gear wheel, where the lever arms are largest and the cross-section is smallest. First, a bending stress arises from the contact force and the lever arm l_1 resulting in $\sigma = \frac{F_K \cdot l_1}{W_B}$.

Second, a torsional stress is generated when the contact force twists the finger with the lever arm $K + 10\,\mathrm{mm}$ resulting in $\tau = \frac{F_K \cdot (K + 10\,\mathrm{mm})}{W_T}$. The shear stress at the critical cross-section, which results from the counterforce of the friction force, is neglected because it remains below $0.1\,\mathrm{N/mm^2}$ even for the heaviest gripped object. The equivalent stress σ_v allows the multi-axial load from torsion and bending to be transformed into an equivalent uniaxial stress state for comparison with the material properties. The occurring equivalent stress is $\sigma_{va} = \sqrt{\sigma^2 + 3\tau^2}$. The safety factor against fracture is the ratio of the permissible equivalent stress from the material datasheet σ_v to the occurring equivalent stress σ_{va} resulting in $S_b = \frac{\sigma_v}{\sigma_{va}}$.

By defining a specific gripping range, the kinematic design of the gripper can be tuned to ensure safe approach, gripping, manipulation, and release. By defining overlapping gripping ranges within a product family, similar objects can potentially be handled with similar grippers. This reduces the number of variants and simplifies platform creation. For evaluation, the grippable diameter D_g is used. The absolute difference between the center distance a and the radius of the object $\frac{d}{2}$ must not exceed 40% of the finger longitudinal length, which corresponds to an angle of ±25° from the neutral position, i.e., $D_g = \frac{|a - \frac{d}{2}|}{0.4 \cdot l} < 1$.

An overview of the bottom-up mappings can be found in Tab. I.

E. Top-down mapping

The bottom-up mappings were implemented in MATLAB as part of a customized SSE toolbox, allowing for systematic evaluation of design alternatives. A top-down mapping can be interpreted as the inversion of a bottom up mapping. For this, the following steps were performed:

1) Random sampling of the design space for each use-case,
2) Computation of S_f, S_z, S_b, and D_g for each design,
3) Visualization whether requirements are satisfied,

TABLE I

Quantities of interest and bottom-up mappings

Variable	Description	Formula for bottom-up mapping
S_h	Safety factor against object falling (grip force vs. weight)	$S_h = \frac{M \cdot i \cdot \mu}{m \cdot g \cdot l}$
S_z	Safety factor against object deformation (contact pressure limits)	$S_z = \frac{q_{max} \cdot K \cdot 3 \cdot l}{M \cdot i}$
S_b	Safety factor against structural failure (stress in finger material)	$S_b = \frac{\frac{F_K \cdot l_1}{W_B} + \frac{F_K (K+10mm)}{W_T}}{\sqrt{\sigma^2+3\tau^2}}$
D_g	Gripping diameter ratio (compatibility across object sizes)	$D_g = \frac{\lvert a-\frac{d}{2} \rvert}{0.4 \cdot l}$

4) Generation of solution boxes where all requirements are fulfilled [7].

Solution boxes are generated manually by adjusting candidate intervals for each DV. Fig 4 shows a so-called selective design space projection. Sample designs assume random values (1) from the design space interval for the design variables shown on the diagram axes and (2) from the candidate intervals of the box-shaped solution space for all design variables. The solution box is approximately valid, when it only includes designs, that satisfy all requirements. When there are still designs included that violate the constraints, visual information guides the user to adjust the candidate intervals to remove them.

F. Identification of commonalities

By overlaying the solution spaces of multiple target objects, regions of overlapping feasibility were identified. These intersections represent opportunities for component reuse across variants. For example:

- A common gear ratio and finger longitudinal length is permissible for both the coffee cup and glass,
- A shared contact pad design is permissible for multiple deformable items,
- Two axis spacing values are necessary to cover all use-cases.

This enabled a reduction of the number of unique parts while all requirements are satisfied. The final gripper family was defined by combining the minimal set of modules required to span the full use-case spectrum.

IV. Results

The evaluation focused on identifying valid configurations across multiple gripping scenarios and optimizing modularity through reuse.

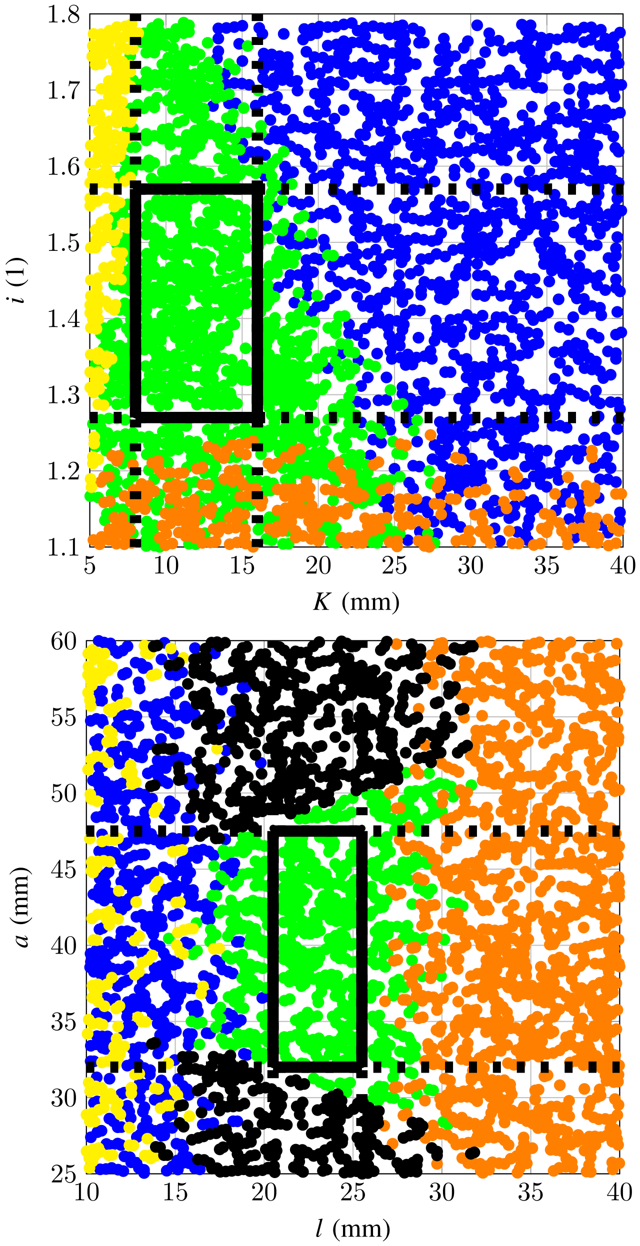

Fig. 4. Projection of sample designs for the coffee mug gripper. Orange designs violate the requirement on the safety against falling, yellow against deformation, blue against structural failure and black violates the requirement on gripping diameter ratio. Green designs fulfill all requirements.

A. Evaluation of gripper performance

Over 10,000 design were evaluated per object type. Every time, candidate intervals were modified manually.

Fig. 4 shows two exemplary solution space projections, plotting the contact pad length K against gear ratio i as well as the finger longitudinal length l against absolute difference between the center distance a. Valid design regions fulfilling all requirements are shown in green.

B. Valid configurations for use cases

Table II summarizes the realized DVs sets for the six objects. Each column represents a gripper configuration that meets all functional and mechanical requirements.

TABLE II

Resulting Design variables for gripper variants

Object	i	l (mm)	K (mm)	a (mm)
Coffee mug	1.4	25	13	45
Beverage can	1.4	37	27	30
Paper towel roll	1.4	37	27	45
Salt dispenser	1.4	37	13	30
Juice glass	1.4	25	13	30
Paper cup	1.4	37	27	30

C. Identification of commonalities

Overlaying the solution spaces of all use cases revealed significant parameter overlaps:

- A single gear ratio $i = 1.4$ was sufficient for all variants,
- Two finger longitudinal lengths ($l = 25\,\text{mm}$ and $l = 37\,\text{mm}$) covered the entire range,
- Contact pad lengths and axis spacings were reducible to 2–3 variants.

This enabled a modular product architecture with only 9 component variants (see Fig. 6) needed to build all grippers for the 6 objects as opposed to the individual gripper development with 21 component variants. Fig. 6 shows the resulting modular product family.

D. Modular system efficiency

The reduction of unique parts contributes to lower design, manufacturing, and inventory costs. The reuse of modules such as actuators and housing units simplifies integration and supports scalability.

Furthermore, the solution space approach ensures that the selected modular configurations satisfy all requirements at a reduced number of component variants. The resulting product family can be seen in figure 7.

V. Discussion and outlook

A. Discussion

The presented results demonstrate the feasibility and effectiveness of combining modular product design with Solution Space Engineering for robotic gripper development. The methodology enabled a quantitative mapping between design variables and functional performance, allowing early-stage decisions based on validated configurations. It is possible that this approach can be scaled up to more complex application scenarios.

The modeling assumptions—such as idealized friction, simplified deformation behavior, and linear material properties—provided a practical approximation suitable for conceptual design. However, the fidelity of the model can be further increased by incorporating dynamic effects, nonlinear material models (e.g., for TPU pads), and tolerance chains.

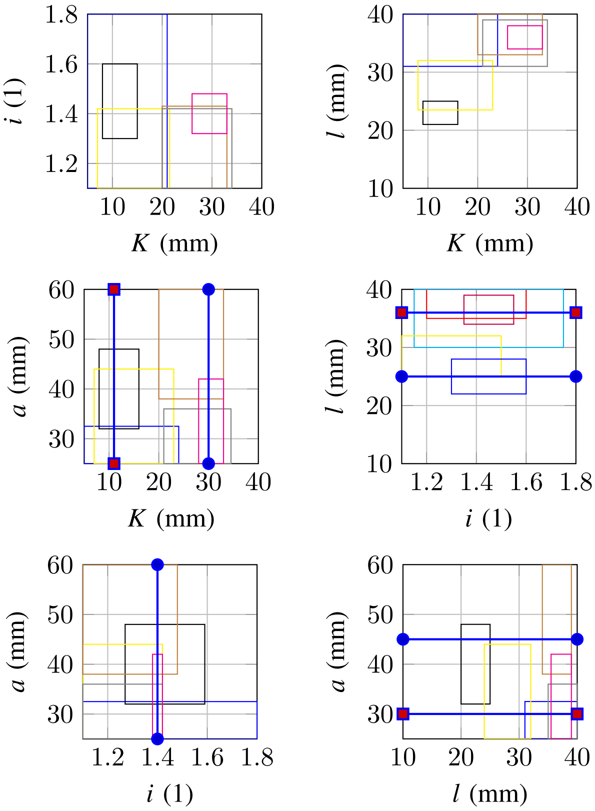

Fig. 5. Overview of the solution boxes for the gripper for a coffee mug (blue), beverage can (magenta), paper towl roll (orange), salt dispenser (blue), juice glass (yellow), paper cup (grey)

Fig. 6. The 9 component variants.

The modular strategy proved successful in reducing internal complexity while maintaining external product variety. In particular, the ability to reuse a fixed actuator and transmission unit across multiple gripper variants significantly decreases development effort and cost.

Limitations include the lack of experimental validation under real-world conditions (e.g., varying object orientations, humidity, or wear), which may affect gripping performance. The toolbox operates under deterministic assumptions, where uncertainties in input parameters are not yet modeled.

Fig. 7. Resulting Product Family

B. Outlook

Future work will focus on extending the presented approach in several directions:

- Experimental Validation: Real-world testing of the gripper variants to confirm modeled grip force, deformation behavior, and structural safety.
- Integration of Sensor Modules: Inclusion of tactile or proximity sensors as modular add-ons to improve situational awareness and enable adaptive gripping strategies.
- Automation of Workflow: Enhancing the SSE toolbox with optimization algorithms or machine learning methods to accelerate the search for valid configurations.
- Lifecycle Considerations: Assessing the modular system from a lifecycle perspective, including maintenance, serviceability, and end-of-life disassembly.

In addition, coupling this framework with cost models and sustainability indicators (e.g., carbon footprint or recyclability) could support more holistic decision-making in early design phases.

VI. Conclusion

This paper presented a model-based methodology for the development of a modular robotic gripper family with a reduced number of component variants. Starting from object-specific requirements, a modular gripper architecture was defined, quantitative modules so-called bottom-up mappings were established, and then inversed to compute so-called solution spaces for each gripper variant. Whenever solution spaces overlap, components can be shared.

The results show that a single actuator platform and a set of interchangeable 9 modules instead of 21 individual ones can fulfill a wide range of 6 gripping tasks.

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