Design of Engineering Systems in Industrial and Enterprise Systems Engineering Department at University of Illinois

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***Abstract*—This paper presents a sampling of research in design of engineering systems in the Department of Industrial and Enterprise Systems Engineering at the University of Illinois at Urbana-Champaign. Recent activity in design principles for actively controlled and autonomous systems, normative decision based design theory and methodology, and bio-inspired compliant mechanisms and soft robotics is presented.**

***Keywords*—design systems; actively controlled systems; autonomous systems; normative design; decision based design; bio-inspired compliant mechanisms; soft robotics**

I. INTRODUCTION

The Department of Industrial and Enterprise Systems Engineering at the University of Illinois Urbana-Champaign offers a PhD program in Systems and Entrepreneurial Engineering in addition one in Industrial Engineering. This unique combination of research programs housed in one Department provides the opportunity for researchers to deeply integrate engineering systems design with advanced mathematical models of their behavior. This paper presents a sampling of the research being carried out in the Department.

II. DESIGN PRINCIPLES FOR ACTIVELY CONTROLLED AND AUTONOMOUS ENGINEERING SYSTEMS

A. Active Autonomous Systems

Design of actively controlled and autonomous engineering systems is a topic of growing importance that spans many application domains, including energy sustainability, transportation, agriculture, and manufacturing. As engineers transition from designing systems intended for human operation, to those with increasing levels of automatic control (or even autonomous capabilities), system design strategies must be reexamined. For example, in agricultural systems, the current strategy for system efficiency is to develop larger machines that can do more with a single human operator. The dominant design constraint is a regulation on the largest vehicle that can be transported along public roads. If agricultural systems in the near future transition to autonomous or semi-autonomous operation, what would be the best system design? Would it perhaps involve a larger fleet of smaller vehicles, all supervised by the same human operator? An answer to this question involves both system-level and vehicle-level design. More importantly, we lack knowledge of design principles for guiding the development of complex systems such as the agricultural system described. A core objective of our research efforts is to discover guiding principles for designing active and autonomous engineering systems. This section summarizes some of our recent efforts to create the foundational knowledge and tools required to address this question. One strategy for investigating the design of active and autonomous systems is to study in detail how the optimal design of a system changes as control authority is gradually increased. For example, a recent study used this approach to investigate how active automotive suspensions should be designed differently from passive systems [1]. A bound on actuator force was varied from zero (passive system) to very large bounds (fully active), and at each point along this transition a system-optimal active suspension design was identified. Each of these suspension designs was then analyzed to identify trends in this transition from passive to fully-active designs. This is illustrated in Fig. 1.

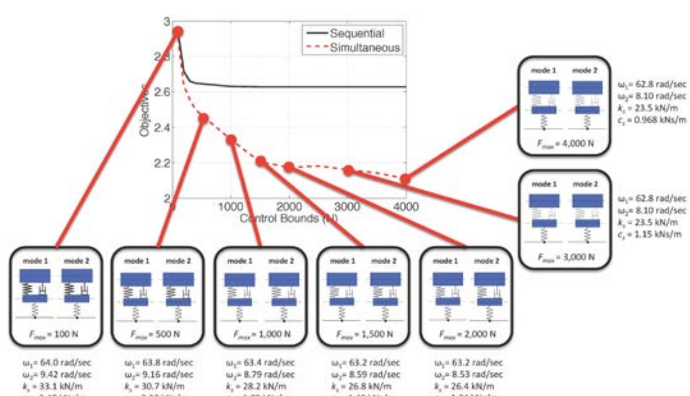

Figure 1. Transition from passive to fully-active suspension system design, and analysis of optimal designs throughout this transition.

This type of study requires that we have a means for identifying system-optimal designs efficiently. When dealing with actively controlled systems, it is imperative to recognize that physical system design and control system design are coupled tasks. More specifically, the best way to design a control system depends on the physical system design, and vice versa. An integrated design approach is required to capitalize on the synergy between these two aspects of system design. Co-design is a class of design methods that addresses this coupling and generates system-optimal designs. As a result, co-design is an essential tool for studying design principles for active and autonomous systems. While a significant amount of work has been done in the area of co-design, including theoretical and methodological developments, much of this work has been performed from a controls-centric perspective that treats physical system design in a very simplified way. Most co-design methods, therefore, have limited utility for studying how the physical aspects of an active or autonomous system should be design differently (which is a central element of the stated research objective).

The above active suspension case study only considers continuous variations in system design. The system architecture remains fixed. This approach is limited in the insights that can be derived since the design space exploration is limited to continuous design changes. The ability to explore system architecture design changes will likely lead to richer insights into learning how active and autonomous systems should be designed differently from conventional systems. In addition, autonomous system operation in many cases makes practical the use of system reconfiguration as a strategy for improving system robustness, or to endow systems with a wider range of capabilities.

Making progress toward the discovery of design principles for active and autonomous systems will therefore require significant developments in a number of foundational areas to more fully support the required investigations. More specifically, these investigations will require 1) co-design methods that skillfully balance depth in both control and physical system design, 2) efficient methods for system architecture design that support rapid architecture design space exploration, 3) rigorous design methods for autonomously controlled reconfigurable systems, and 4) physical design test-beds that are useful for evaluating co-design methods. The remainder of this section summarizes progress in these four areas.

B. Balanced Co-Design

Simultaneous design of a physical system and its controller (co-design) can lead in some cases to dramatically superior performance compared to conventional sequential design methods. Much of the existing work in co-design, however, embraces a controls-centric perspective. One common result of a controls-centric approach is a simplified treatment of physical system design, often involving unrealistic design models. Significant gaps are being addressed by taking a balanced approach that treats physical system design in a more comprehensive way, further exploiting synergy between physical and control system design (e.g., capitalizing on passive system dynamics).

Direct Transcription (DT) is an optimization method with proven effectiveness for solving challenging optimal control problems. It is based on nonlinear programming, but instead of nesting simulation within optimization, simulation and optimization are performed simultaneously. Our work in the last few years has demonstrated that DT is a critical element of balanced co-design, as it allows the inclusion of nonlinear inequality constraints [1, 2]. These constraints are essential for realistic physical system design as they can be used to model important failure modes. Past co-design studies used physical design problem definitions that were so simplified that failure modes and inequality constraints were not used. These simplified problems and the absence of inequality constraints led researchers to believe that co-design problems had unidirectional coupling (i.e., control design depends on physical system design, but not vice versa). Associated theoretic developments depend on the absence of inequality constraints and on the presence of unidirectional coupling. We have demonstrated recently that co-design problems in fact have bidirectional coupling, and that inequality constraints are required for realistic treatment of physical design [3, 1]. These discoveries motivate the creation of a completely new approach for co-design. We have developed new balanced co-design methods that leverage the power of DT to manage inequality constraints, while dealing with the complexities of new problem structures.

One important challenge in balanced co-design is incorporating high-fidelity physics-based models of engineering systems to support more detailed physical system design problems. The computational expense of these models often makes the application of co-design impractical. Numerous techniques have been developed for optimization based on computationally expensive models, such as surrogate modeling.

Conventional surrogate modeling approaches, however, use generalized approximation functions that cannot capitalize on the unique properties of dynamic system design problems. We have developed a completely new surrogate modeling approach for dynamic systems to support the use of high-fidelity models in co-design studies. This new method, Derivative Function Surrogate Modeling (DFSM), creates surrogate models of just the time derivative function for a model. This enables rapid simulation and fast overall convergence. Initial results have shown an order of magnitude reduction in function calls required to solve co-design problems based on high-fidelity system dynamics models [2]. DFSM is useful in cases where computational expense is primarily due to derivative function evaluation as opposed to large state dimension.

C. System Architecture Design

System architecture (or topology/configuration) design is particularly challenging for dynamic systems. Fair comparison between candidate architectures requires solution of a co-design problem for each candidate architecture. Exhaustive enumeration has been used to explore architecture design, but is limited to very small systems. Heuristic filtering methods are limited as well. Genetic algorithms have been applied, but cannot be used directly to solve problems with variable dimensionality, and have difficulty scaling to large systems. **Generative algorithms**, widely used in generative art (Fig. 2), are being explored as a means to explore the architecture design space efficiently, including the ability to investigate topologies with varying dimensions.

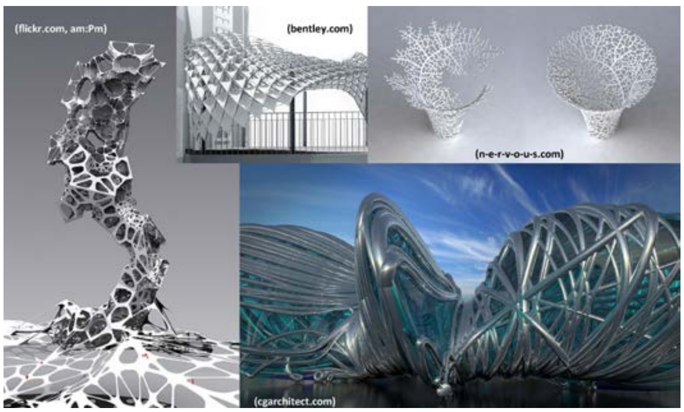

Figure 2. Generative Algorithm Results

We have created new generative algorithm based design methods for structural optimization, hybrid powertrains, genetic regulatory networks, and other systems that can embed design requirements within the algorithm to support highly efficient design space exploration [4]. This approach to system architecture design permits the optimization of large-scale systems, unapproachable using standard methods. The generative algorithm design strategy is compared graphically to 1) enumeration-based architecture design, and 2) directly encoded genetic algorithms in Fig. 3. Several approaches may be used to identify the best system architecture design for a given situation. In each case, an inner-loop optimization problem is solved for each candidate architecture design to ensure a fair comparison (i.e., we only use the best possible instance of each candidate for comparison). Exhaustive enumeration (left) will produce a globally-optimal solution, but is limited to only very small system design problems. Genetic algorithms (center) can be an efficient strategy, but break down as system dimension increases or varies. A generative algorithm approach (right) abstracts the architecture design representation as a set of generative algorithm rules. This enables the genetic algorithm to search the design space much more efficiently, supporting the design of large-scale systems.

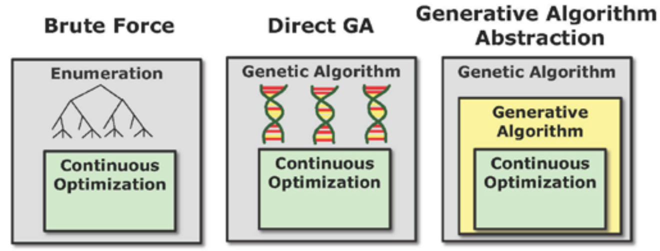

Figure 3. Enumeration-based, Directly Encoded and Generative Algorithms

D. Design for Reconfigurability

We are developing design methodologies for several classes of reconfigurable systems, including continuously reconfigurable systems (reconfigurable delta robot for agile manufacturing, reconfigurable testbeds for co-design methods), and multimodal reconfigurable systems (multimode hybrid powertrains, electrical power networks, origami-based design) [5].

E. Physical Implementation in Design Research

Much of the work performed by the design research community is based on virtual design models (simulation, CAD, etc.). While these studies provide important insights, they should be complemented by studies involving physical implementation of the systems being designed. This is important for two reasons: 1) physical implementation reveals complexities that must be managed that are hidden when using simulation only, and 2) it is essential that the next generation of design researchers (i.e., current graduate students) have an understanding of what is required to design a system completely and manufacture it. Several of our projects involve physical implementation, often for the purpose of validating design methods, and in some cases in the creation of new technologies. We are developing reconfigurable testbeds that allow researchers to rapidly change physical system properties so that co-design results (i.e., physical and control system design specifications) can be tested easily.

F. Application Domains

The following application domains have been used in the study of the above research topics: Wave Energy Converter Design, Wind Turbine Design, Hybrid and Electric Vehicle Powertrain Design, Active Automotive Suspension Design, Robotic System Design, Synthetic Biology (genetic regulatory network design), Design of Rheologically Complex Fluids, and Structural Systems: (design of space observatories, structural topology optimization).

III. DESCRIPTIVE VS. NORMATIVE DESIGN THEORY AND METHODOLOGY

A. *Descriptive vs. Normative Tension*

Previous work [6-10] revealed the importance of considering market-based issues during design. This typically requires making tradeoff decisions under uncertainty, which can be very difficult. Human expert designers have developed heuristic "rules of thumb" to aid in this task, but these heuristics can inadvertently lead to systematic cognitive biases that lead the decision maker away from the best choice. This project addresses the tension between descriptive and normative approaches to design systems [11]. Descriptive approaches typically seek to document, formalize and/or automate existing ad hoc design methods used by experts, towards the goal of making current best practices available to all. In contrast, normative approaches attempt to improve upon existing design practices, towards a new method for how design should be done. Both approaches have strengths and weaknesses, as shown in Table 1.

TABLE 1. Descriptive vs. Normative Design Methods

	Descriptive	**Normative**
Goal	Make best practices available to all	Improve on best practices
Methods	Holistic model of whole system Documents best practices of experts	Abstract model of selected elements
	Immersive Computing Environments	Mathematical models Optimization Decision based design
Strengths	"Rings true" Feels familiar to practitioners	Optimal solution is most efficient use of resources Axiomatic foundation provides basis for belief this is the best possible solution
Weaknesses	Can inadvertently embed mistakes, inefficiencies, cognitive biases	May be difficult to get buy-in
	Cannot tell if solution is the best possible (optimal)	Need to gather or estimate large amount of input parameter data Can inadvertently embed cognitive biases in model formulation or input parameter estimation
	Designer does not necessarily know what to do within system	Can be computationally intractable
Evaluation Metric	Does it mimic reality? No need to judge or evaluate	Are the design and/or process better than before?

This project seeks to resolve some of the tension between the two approaches. The goal is a new method for designing a design system that achieves synergy between normative and descriptive approaches, by exploiting the strengths and remedying the weaknesses of each approach.

The framework shown in Fig. 4 builds upon new advances in immersive computing technology to support early design decision making. New methods of interacting with product data while still in the early design phase can be used in conjunction with descriptive methods to enhance decision making. Figure 4 illustrates how providing the designer with descriptive data and the ability to explore normative methods while interacting with full scale CAD models in an immersive computing environment will bring both descriptive and normative methods together to improve the entire design process.

B. *Framework*

Figure 4 outlines the cyclic nature of the framework. The connections between each of the elements indicate the synergistic nature of the method. The Immersive Computing Technology (ICT) environment can be employed to quickly gather information and data from a simulated "experiment" much more quickly than would be possible with physical prototypes. ICT also affords the collection of data unavailable in traditional design environments. Conversely, users of the ICT system could be provided with a visual abstraction of a normative mathematical model and/or sensitivity analysis results in order to guide their activities within the system towards those that might be more productive. Visualizations can also be employed to debias the user. The end goal is to achieve a feasible disassembly plan that accommodates several trade-off decisions that might not be immediately apparent from simply viewing the CAD models using traditional computing interfaces.

Starting with the descriptive approach, an immersive computing environment is created in which the designer can view, manipulate and interact with the design artifact and also execute any operations of interest, such as assembly, product use by the consumer, or disassembly at end-of-life. This approach sometimes seeks to mimic physical reality as closely as possible in order to capture all the important aspects of the interaction between the design artifact and the user. ICT has been mainly used to explore different design solutions rather than telling which solution is optimal. The designer is free to explore the design through emulation of natural physical interaction, as he or she might with a prototype. At this stage, heuristic rules of thumb are often employed based on the designer's prior experience. These heuristics are necessary and useful, but can inadvertently be influenced by cognitive biases. Then the question "Can we do better?" is asked. A normative approach is employed in order to improve on the designer's experience and insert some formality into a somewhat ad hoc implementation of best practices. By definition, this approach seeks to improve upon existing ad hoc best practices, and often employs a mathematical abstraction of the most important cause-and-effect elements of the design problem.

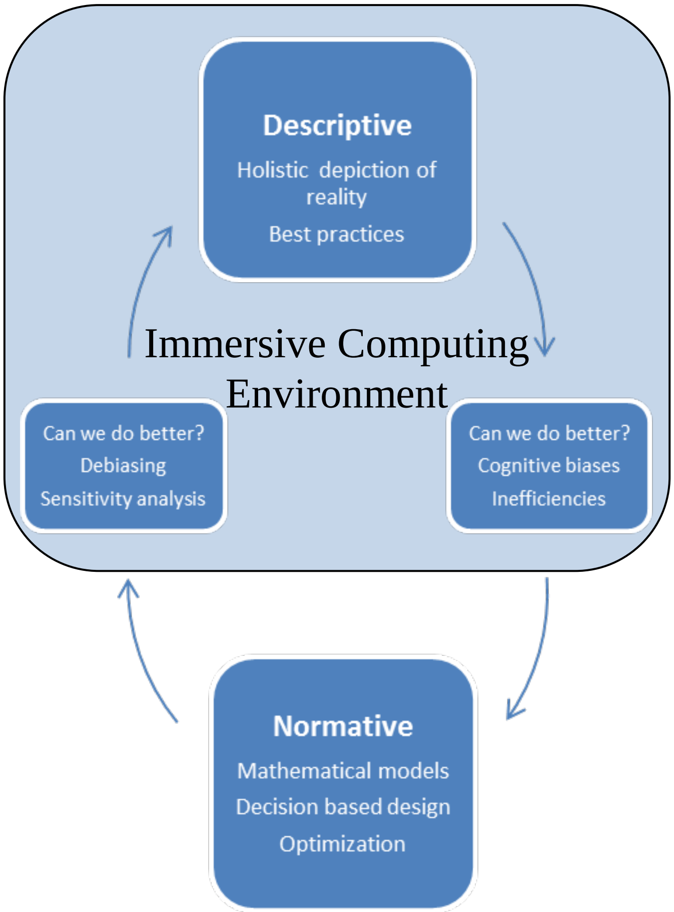

Figure 1. Achieving Synergy between Descriptive and Normative Design

Mathematical models are an abstraction of reality, and the analyst must first determine which aspects of reality should be included in the model and which should not. This requires answers to questions such as "What are the objectives? What are my options? What tradeoffs am I willing to make? What design decisions can I control in order to achieve the objectives?" After the model is formulated, estimations of the input parameters are required. Interacting in the ICT can serve to provide input data to the mathematical model. The user can manipulate the product and generate data that will inform both the formulation of the mathematical model and the use of the results.

The results of mathematical models often include not only the optimal solution, but also sensitivity analysis of the result. At this stage, the designer has the advantage of querying the available results from the normative methods while still interacting within the ICT. Results from sensitivity analysis can be displayed to the designer to inform his/her decision making. Instead of relying on capturing all aspects of the design in the mathematical model, the user can test the boundary conditions of the model and improve upon it by manipulating and interacting with the early product design in the ICT. Combining natural interaction in the ICT with formalized mathematical models allows the designer the ability to leverage both the descriptive and the normative approaches to design. Then the cycle of design continues. Again, the question is asked "Can we do better?" At this point, methods can be employed that will serve to identify cognitive biases and means to alleviate these biases. The ICT provides a unique environment upon which to implement these approaches.

Figure 5 shows an example of an ICT environment that includes both a CAD based model of a product that is being evaluated by a user for a variety of possible disassembly operations sequences. Using 3-D glasses, the user can "manipulate" and move each component with the wand, exploring alternative disassembly sequences. This "real life" experience is enhanced with a visualization of a disassembly sequence presence graph. This visualization is comprised of nodes (spheres representing disassembly configurations) and edges (line geometry representing disassembly transition opportunities) connecting the nodes.

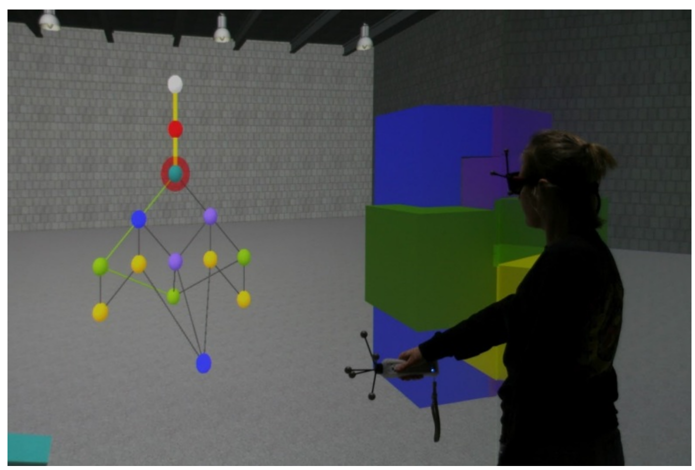

Figure 5. Example ICT disassembly environment with precedence graph visualization aid

IV. A Design Methodology for Bio-Inspired Compliant Mechanisms and Soft Robotics

A. *Compliant Mechanisms and Soft Robotics*

Bio-inspired compliant mechanisms and soft robotics are an emerging engineering systems field that require new methods for design. Traditionally, engineers are inclined to design machines, robots and products using multiple structural modules connected through joints or interfaces. Each module is made stiff and rigid in order to make them strong. However, nature divulges a paradigm where unprecedented functionality is achieved through distributed material deformation with no distinct interfaces. Elephant trunks, octopus arms, snakes and grapevine tendrils are examples of nature's compliant adaptive structures that are by no means considered weak, as shown in Fig. 6.

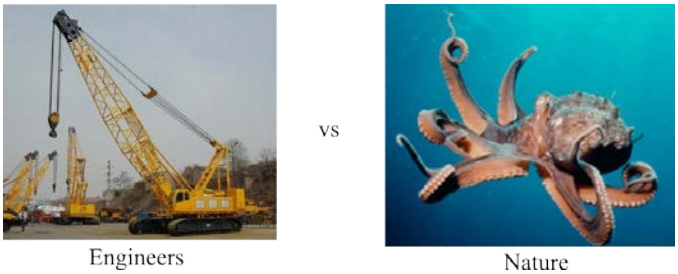

Figure 6. Contrasting an engineer's stiff and strong design with nature's flexible, yet strong designs

Distributed compliance is thus a bio-inspired design paradigm that negotiates two seemingly antithetical features, namely *flexibility* and *strength* [12-14]. Our research focuses on incorporating distributed compliance into robotics [15-20], product design [21], microsystems [22] and rehabilitation [13] and several applications by creating systematic tools for their synthesis.

The behavior of compliant systems are governed by the strong coupling between elasticity and large deformation kinematics [23-24]. Thus traditional synthesis methodologies used computationally expensive algorithms to deal with this coupling and generate designs that matched specifications [25-26]. However, the resultant designs suffered from numerical artifacts and in some cases, were not manufacturable. Thus, there is a growing need for insightful conceptual synthesis techniques, where guidelines are proposed to enable “pen and paper sketches”, with little or no need for computation.

B. *Representation of Compliance*

The key enabler for such a methodology is the representation of compliance that lends itself to analyzing the deformation behavior of compliant mechanism topologies and the synthesizing topologies from a given specification with relative ease. We proposed such a kinetostatic representation [23-25] that enables load flow visualization between input and output of a compliant mechanism. The magnitude and direction of load flow in the constituent members enables functional decomposition of the compliant mechanism into (i) Constraints (C): members that are constrained to deform in a particular direction and (ii) Transmitters (T): members that transmit load to the output. Furthermore, it is shown that a constraint member and an adjacent transmitter member can be grouped together to constitute a fundamental building block known as an CT set whose load flow behavior is maximally decoupled from the rest of the mechanism. Figure 7 shows how a compliant mechanism with a supposedly complex topology was first analyzed for its load flow behavior, and then decomposed into constituent building blocks. The deformation of each building block can be studied using simple elastic equations. Using the insight gained from the above analysis, a design methodology was developed where the user conceptualizes the load flow paths that can meet certain kinematic specifications. Based on the load flow paths, common pre-characterized building blocks can be assembled along the load paths. Thus, the load flow formulation is intuitive for analysis and synthesis.

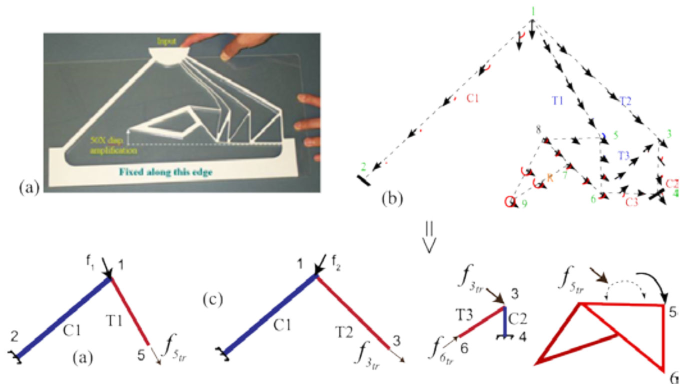

Figure 7. Subdividing a complex compliant mechanism topology into building blocks by assessing the nature of load flow. Members with axial load flow are transmitters(T) and transverse loads are constraints (C). A building block consists of one transmitter and one constraint.

C. *Compliance Metric*

The conceptual synthesis elucidated above yields a topological representation of a compliant mechanism geometry. In the next step, actual dimensions must be associated with the mechanism and analyzed to determine its behavior. It is in this step that manufacturability and stress considerations are imposed to ensure the practicality of the solution. Furthermore the mechanism must optimally distribute for its compliance, i.e. it must be strong and flexible. We have developed an optimization based refinement process [12, 14] to achieve these attributes. A key enabler for this method is the distributed compliance metric, which is expressed in terms of the volume fraction of the material that is maximally utilized in load bearing and input-output energy transfer. A large value of the metric indicates that the mechanism can attain larger deformation, perform more output work and/ or require minimum material volume for the same failure stress. The implication of metric is seen in Fig. 8.

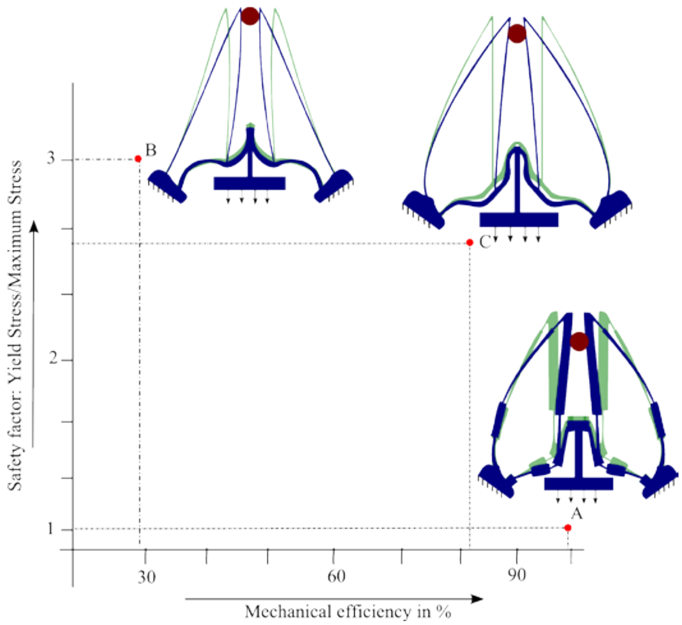

Figure 8. Designs obtained by maximizing the distributed compliance metric (C) maximally overcome the trade-off between minimizing stresses (B) and maximizing mechanical efficiency (A)

The gripper is designed with three primary criteria: (a) mechanical efficiency (b) minimize overall stress, (c) the distributed compliance metric. It is seen that in the first case, the resulting design (A) consists of lumped flexural hinges that deforms, while the majority of the geometry consists of rigid regions. This design, as expected has a high mechanical efficiency, but low safety factors or high stresses. Maximizing stress distribution alone drastically shifts the resulting design (B) to higher stress factors (or lower stresses) but compromising heavily on the efficiency. Maximizing the distributed compliance metric leads to a resulting design (C) that has both high mechanical efficiency and safety factor (low stresses), thus maximally overcoming the tradeoff. This design is a demonstration of simultaneously achieving high strength, flexibility and functionality.

D. *Soft Robotics*

Current research activity lies in realizing soft, dexterous, adaptable robots that can maneuver around environments and manipulate objects that are unstructured. Towards this, novel structural and actuation concepts using inextensible fibers, pressurized fluids and stretchable surfaces that inherently provide these features have been developed. These Fiber-Reinforced Elastomeric Enclosures (FREEs) are inspired by the recurrent design in literature known as Pneumatic Air Muscles (PAMs) used in prosthesis and soft robots owing to their high energy density. *For the first time, Krishnan et al. [16-19] have mapped the kinematics of a large class of cylindrical FREEs with two families of helical fibers* as shown in Fig. 9.

By using geometric relations arising from inextensibility of fibers and incompressibility of fluids, simplified models that estimate deformed shape, force exerted, and relative stiffness of actuators have been developed [16-19]. Based on the relative helix angles of the fibers, the attainable motion can be divided into a combination of rotation (R), extension (E) or compression (C) deformation types.

Of these, the Extension-Compression line (in red in the top panel of Fig. 9) constitutes the Pneumatic Air Muscle. This wide unexplored design-space has enabled a user-insightful design methodology to systematically combine two or more actuators with different fiber configurations in parallel to achieve any deformation pattern [18].

Figs. 9 (bottom panel) and 1g show how a combination of two and three actuators respectively can attain independently controllable deformation patterns. These patterns have been demonstrated in Fig. 9 towards manipulating an unstructured object. The advantage of these designs over existing soft manipulators (such as OctArm [27]) is the ability to maintain large workspace without the need for series architecture of actuators, thereby minimizing the effect of gravity.

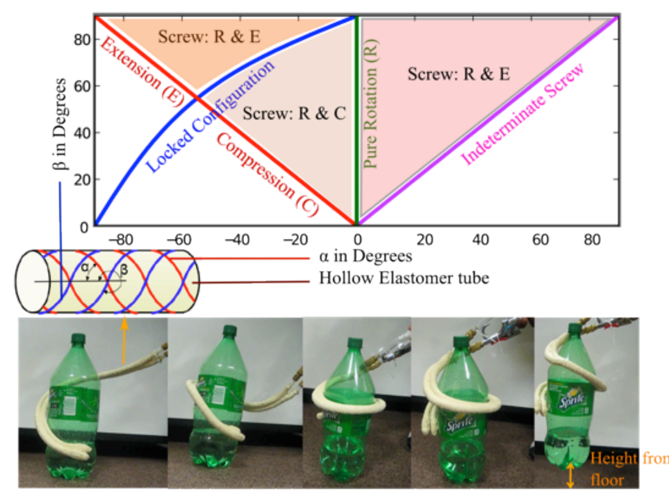

Figure 9. Using the wide unexplored design space for fiber-reinforced elastomeric enclosures to realize dexterous, adaptable manipulation

Furthermore, such purely parallel architectures can be successfully miniaturized for potential use in minimally invasive surgery. There are a number of research challenges to effectively realize the capability of these soft, dexterous, and adaptable robots that will be addressed in ongoing and future research. These include a (i) robust design methodology to determine the fiber angles that can lead to large workspace, dexterity and maneuverability, (ii) sensing techniques for shape estimation, and (iii) task planning and automation.

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