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EMBEDDED SENSORS AND FEEDBACK LOOPS FOR ITERATIVE IMPROVEMENT IN DESIGN SYNTHESIS FOR ADDITIVE MANUFACTURING

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ABSTRACT

Design problems are complex and not well-defined in the early stages of projects. To gain an insight into these problems, designers envision a space of various alternative solutions and explore various performance trade-offs, often manually. To assist designers with rapidly generating and exploring a design space, researchers introduced the concept of design synthesis methods. These methods promote innovative thinking and provide solutions that can augment a designer's abilities to solve problems. Recent advances in technology push the boundaries of design synthesis methods in various ways: a vast number of novel solutions can be generated using high-performance computing in a timely manner, complex geometries can be fabricated using additive manufacturing, and integrated sensors can provide feedback for the next design generation using the Internet of things (IoT). Therefore, new synthesis methods should be able to provide designs that improve over time based on the feedback they receive from the use of the products. To this end, the objective of this study is to demonstrate a design synthesis approach that, based on high-level design requirements gathered from sensor data, generates numerous alternative solutions targeted for additive manufacturing. To demonstrate this method, we present a case study of design iteration on a car chassis. First, we installed various sensors on the chassis and measured forces applied during various maneuvers. Second, we used these data to define a high-level engineering problem as a collection of design requirements and constraints. Third, using an ensemble of topology and beam-based optimization techniques, we created a number of novel solutions. Finally, we selected one of the design solutions and because of some manufacturability constraints we, 3D-printed a prototype for the next generation of design at one third scale. The results show that designs generated from the proposed method were up to 28% lighter than the existing design. This paper also presents various lessons learned to help engineers and designers with a better understanding of challenges applying new technologies in this research.

INTRODUCTION

In the current design of engineering products, designers, instead of exploring a space of various alternative solutions, often rely on previous designs to create the next generation of products. This process hinders design creativity and discourages designers to find innovative solutions [1]. This lack of out-of-the-box thinking is one of the reasons that engineering products have a similar pattern to their design. For instance, a configuration study on twin-engine propeller-driven aircraft reported that the baseline design accounted for 66% of all configurations [2]. This limitation in designers' creative thought by adhering to a pre-established set of ideas in the design process is known as design fixation [3]. Fixation leads to duplication of efforts and makes a design process difficult to adapt to new innovations in the field [4].

To reduce fixation and exploit inventive design, designers create a space of various alternative solutions and explore various performance trade-offs. To assist designers with rapidly generating a design space, researchers introduced the concept of design synthesis methods [5]. These methods promote innovative thinking and provide solutions that can augment a designer's abilities to solve complex problems. These techniques have been tested by generating a number of novel yet feasible designs such as aircraft configurations [6], wheel rims and cooling fins [6], satellites [7], power trains [8], and gear boxes [9, 10]. One of the limitations of the current synthesis methods is that they do not generate solutions based on usage feedback, which is crucial for iterative improvement of products.

With widespread availability of IoT technologies, product designs can now be cheaply and effectively instrumented to gather data on usage patterns over long time spans and large amount of users. Therefore, new synthesis methods should support leveraging sensor data and generating novel solutions not only for one generation of product design, but also for extensions of a product lifecycle, improving the correlation between analysis models and real performance metrics. To this end, the objective of this study is to demonstrate a data-augmented design synthesis approach that, based on usage pattern gathered from sensor data, generates numerous alternative solutions targeted at additive manufacturing.

RELATED WORK

Developing means of generating a large number of alternatives that satisfy design requirements is known as design synthesis [5]. To synthesize design problems, researchers mainly focus on generating solutions based on functions, grammars, or analogical knowledge. In function-based synthesis, designers decompose the intended functionality of a design problem into sub-functions and generate conceptual solutions that satisfy product functionality [5] [11]. In grammar-based design synthesis, designers define a language of design –including vocabulary and rules—to transform their initial design into various novel solutions [5] [12]. The analogy-based design methods (e.g. biologically-inspired design) develop solutions by drawing inspiration from previous design knowledge [5] [13].

Product design using design synthesis methods requires three main steps (Figure 1). First, designers need to appropriately define their problem. Then, they should select and apply appropriate synthesis techniques to their problem and generate a space of solutions that satisfies all of the design requirements. Finally, designers need to select and fabricate their product at the end of the design process.

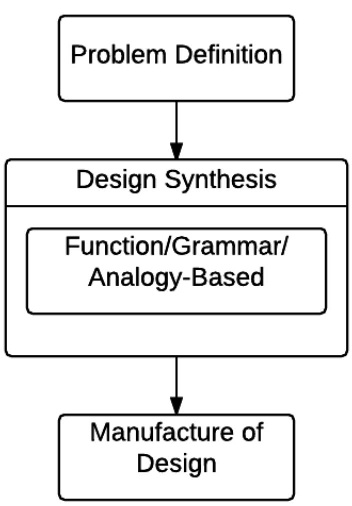

Figure 1. Current synthesis methods

A number of studies focus on improving the synthesis methods for designing products. For instance, developing various grammar rules for creation of function structures in product design [14], creating rules for the design of sheet metals [15], defining vocabulary and rules for automating satellite design [7], and improving the quality of design rules by analyzing them in the development phase rather that during their application [9]. These studies exhibit three fundamental limitations. First, they have been demonstrated to be effective on a single generation of the product design cycle. In practice, most successful products have multiple generations and evolve from one generation to the next. Design synthesis based on rules and grammars may produce a completely different design in each generation, which may lead to increased uncertainty in the design selection process. Second, applying grammar rules or creation of function structures requires tools and expertise that is not generally available in the current product design practice [5]. Finally, current synthesis methods cannot directly incorporate any usage feedback of the designs they generate: in each product generation, designers manually analyze usage feedback data and based on their intuition attempt to incorporate improvements to their products. At time of writing, we could not find in the literature any synthesis method capable of generating improved design solutions based on the usage feedback of products.

PROPOSED METHOD

The method proposed in this study extends the current design synthesis techniques to be applied beyond the conceptual design stage for improving multiple generations of products based on usage feedback (Figure 2). Given an initial product design, our method requires putting it through sets of controlled design trials to capture its performance and behavior characteristics. Data are collected using both sensors that are already embedded in the design and additional sensors applied to the design ad-hoc for the controlled experiments. In addition, a 3D model of the design is captured and used to identify locations of boundary condition and obstacle for the design space. Next, the usage data are analyzed for the problem definition stage in which users define their high-level engineering problem as a collection of design requirements and constraints. In the next step, an ensemble shape synthesis algorithm, composed of topology and beam-based optimization algorithms, synthesizes various geometries based on the combination of volume constant and number of iterations in the topology optimization with density and degree of connectivity in the beam-based optimization. Designers then select and fabricate their design, which forms part of the input for the next design generation.

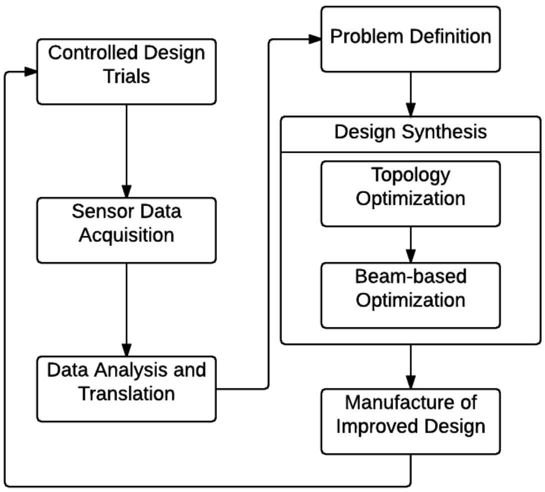

Figure 2. Proposed synthesis method

IMPLEMENTATION OF THE PROPOSED METHOD

We extended the Dreamcatcher prototype generative design system developed by Autodesk Research [16] and selected a case study to implement, test and validate this methodology. We chose to design a small car chassis (10 ft. in length, 4 ft. in width and 2 ft. in height) due to the structural nature of the design problem which suits our current design synthesis prototype system, the ease of fabrication using conventional steel space frame welding methods which allows for fast experimentation, and the potential to draw comparisons with well-established design practices present in the automotive industry. Because of the suitability for design synthesis methods previously developed by the authors and the long-range impact that this study could have on improvement of automobile design and manufacture.

In this paper, the term 'port' refers to the interface of synthesized geometry with external components. The term 'obstacle regions' is used to represent a geometric domain in a design space that syntheses algorithms cannot generate geometry inside of. The term 'initial chassis' refers to the first generation of a chassis designed and engineered for the case study. The following sections describe how each step of the method has been implemented and tested.

Controlled design trial

The initial design was produced using welded chromoly (41xx steel) tubes constructed by domain professionals in the field of automotive fabrication. Since the model defining the design problem for synthesis required a high-fidelity 3D model of the existing geometry and all connected parts for the chassis, a high-resolution polygonal mesh of the initial space frame chassis design and its connected components was obtained by employing a laser scanning method (Figure 3). Planning for sensor data capture was coordinated with the high-resolution mesh to install strain gauges at appropriate locations on the initial design. Preparation for the shape synthesis algorithm required a closed, manifold mesh representation in order to produce valid results and the mesh was decimated and separated from the overall chassis to include only the essential geometry that interfaces directly with external components.

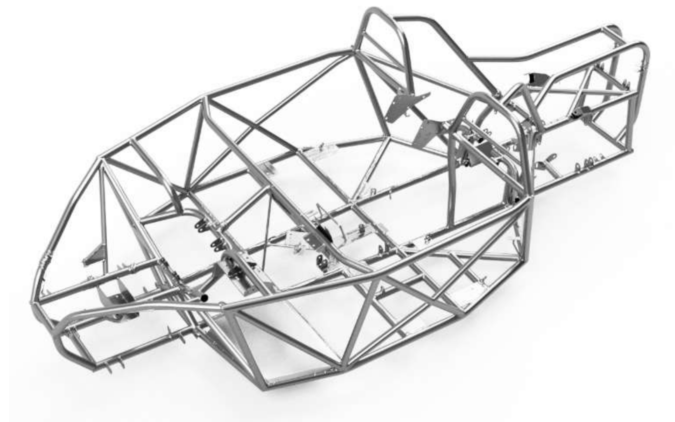

Figure 3. High-resolution mesh created from laser scan of initial chassis design

Sensor Data Acquisition

The sensors were placed in locations where boundary conditions exist due to mechanical contact with other parts (e.g. suspension components). Limitations on the mounting position of the strain gauges required the values reported to be normalized with respect to the orientation of the sensors. Figure 4 shows the typical installation for the strain gauge sensor as installed on the chassis before the road test. A total of 24 sensors were installed at the interfacing mounts of the initial chassis before data acquisition.

After being outfitted with the full sensor package, the chassis was driven in the California desert at extreme conditions by professional stunt drivers (Figure 5). A total of 20 trials were performed where sensor data were collected, where the driver operated the vehicle in scenarios including maximum acceleration and deceleration, hard bank left turn, impact from rough terrain and vehicle at rest. The data from the time trials were inspected and converted into a format suitable for entry as load cases within Dreamcatcher, the generative design tool.

Figure 4. Strain gauge sensors as installed to suspension arm of initial chassis design

Figure 5. Initial design fully equipped for testing with drivetrain and sensors installed

Data Analysis and Translation

We used an Excel plug-in from National Instrument known as TDM-Excel for data analysis and translation. We reconciled all of the sensor data and computed forces applied to the chassis in tension, compression, and shear. This set of load profiles is an essential component for the problem definition step in our design synthesis system.

Problem definition

The laser-scanned geometry of the chassis linkage interfaces and the acquired sensor data were then used to build the problem definition, which involved establishing boundary conditions and obstacle regions. Boundary conditions were described by applying load conditions to all mounting points which the chassis featured, including mounts for seats, shocks, A-arms, engine, transmission, differentials, radiator, tank, instrument panels, and steering wheel. Autodesk Memento was used to subdivide the 3D scan of the chassis to extract the mesh geometry of these mounting points, which can be seen in Figure 6 along with a scan of the engine in its intended position. The location of the mounting points was then adjusted in order to account for an improved suspension geometry, narrower and longer body, and a different engine. In order to accelerate the design synthesis, the geometry of ports was simplified and an enveloping geometry was modeled to encompass several interfaces simultaneously, as can be seen in the results. Load cases for each port were defined by indicating the direction and magnitude of the maximum force experienced by the chassis, calculated from the strain gauge data. Missing loading information was inferred from the weight of the part being mounted plus a safety factor. Lastly, obstacle regions were defined using the meshes of scanned components, such as the engine and the transmission, and by identifying keep-out zones necessary for the use, assembly, and maintenance of the car.

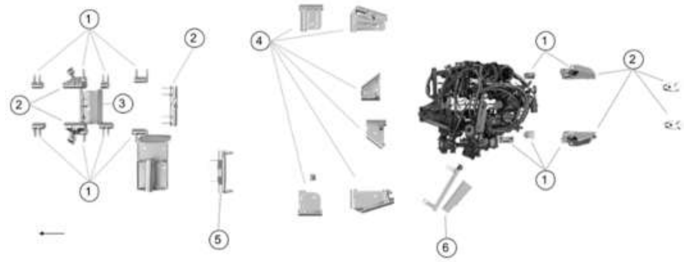

Figure 6. Top view of the location of the interface geometry with the scanned engine block in the rear of the chassis. (1) A-arms, (2) shock mounts, (3) steering rack mount, (4) seat mounts, (5) steering column mount, (6) fan mount.

Design Synthesis

Given the above problem definition, our goal was to synthesize a solution space from which the user could select their preferred final design. We employed a novel synthesis method that combines a topology optimization initialization with a beam network optimization. The topology optimization initialization allows us to preemptively carve away volume that does not support the loads specified in the problem definition giving us a reduced initial space to fill with the beam network. We ultimately used the beam network since this best modelled the chromalloy tube network that was the preferred manufacturing method for the car chassis based on our construction capabilities. The parameters of this method that defined our space were: μ, n, ϵ, η where μ is the topology optimization volume constant that determines the 'thickness' of the solutions, n is the number of topology optimization iterations, ϵ is the density of the beam nodes and η is the degree of connectivity of the beam nodes. The overall algorithm is outlined below and in Figure 7.

Synthesis Algorithm

1. Initialize design space volume Ω with convex hull
2. Generate solution space
    a. Iteratively topology optimize:
        i. Compute strain energy density using finite element analysis (FEA) solver
        ii. Advect volume according to shape derivative
    b. Initialize beam network
        i. Sample beam nodes within volume
        ii. Connect nodes to form beams, discarding invalid beams
    c. Optimize beam network thicknesses
3. User selects optimal design from solution space

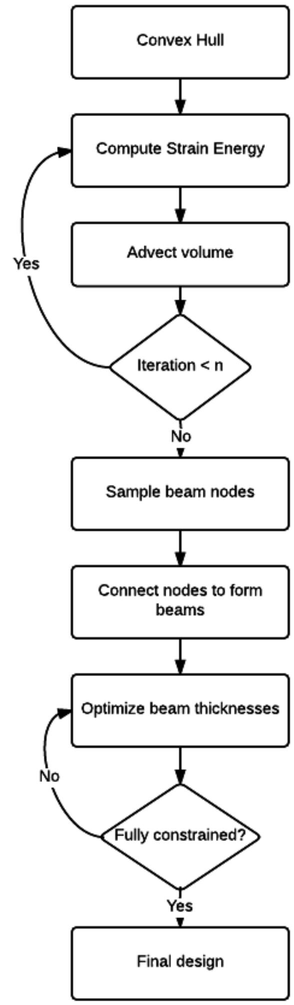

Figure 7. Design Synthesis Flow

To begin the optimization we generated an initial volume Ω by computing a coarse convex hull that included all of the boundary conditions and excluded obstacle regions. This volume was then used as input to the topology optimization. We applied the level-set method [17] [18] since it does not suffer from 'checker-boarding' artifacts of Solid Isotropic Material with Penalization (SIMP) based methods and is a more physical representation of the volume boundary since there are no partial density voxels as in SIMP. We used a hexahedral element-based Finite Element Analysis to evaluate the compliance of the body along with a volume penalty term scaled by the volume constant μ:

$$J(\Omega) := \int_{\Omega} Ae(u_\Omega) : e(u_\Omega) dx + \mu Vol(\Omega), \qquad (1)$$

where A is the elasticity tensor and $e(u_\Omega)$ is the linearized strain tensor of the displacement u_Ω. From this we obtained a shape derivative that enabled us to advect the level-set such that we move in a descent direction at each iteration and are thus able to minimize $J(\Omega)$. We chose μ to be relatively small since the output volume was to be used as a seed for the next stage and a 'thicker' volume was preferable.

After running topology optimization for n iterations, we took the output volume and used this to seed the synthesis of a light-weight beam network. We determined the positions of nodes within the volume using pseudo-random volumetric sampling with the specified density ϵ and then connected the nodes to their nearest ηneighbors to form the initial beam network. Invalid connections were then pruned such that no beam crossed existing geometry or boundary conditions. The boundary condition geometries were kept as surfaces and additional beams were used to connect these surfaces to the rest of the network. The beam thicknesses were then iteratively optimized using the gradient-free, fully constrained method of [19] while ensuring that no member's stress exceeded the yield stress safety factor. During optimization some beam elements' thicknesses dropped below printable limits and were thus discarded from the final design.

Manufacture of Improved Design

Various methods of manufacture were evaluated for the production of the chassis following design synthesis. The complexity of the synthesized form led the team to focus on two main strategies including welded steel tubes and additively manufactured steel. An approach using welded steel tubes was considered with 3D printed 'junctions' serving to rapidly assemble the intersections of commonly available steel tubes. An alternative approach using an Electron Beam Additive Manufacturing machine, Siacki EBAM 300, with the chamber size of 300" (7620 mm) x 108" (2743 mm) x 132" (3353 mm) was also explored. The unique topology of the structure to be printed required inspection from various manufacturers specialized in the equipment used in production. Estimation and feasibility analysis was performed on each method of production and the decision was made to move forward with evaluating scale models of the designed chassis printed in an alternative material for further inspection prior to moving forward with the full-scale improved chassis.

RESULTS

This section presents the results of data acquisition, ensemble synthesis methods, and manufacture of improved design.

Data Acquisition

We used National Instruments DIAdem [20] to quickly inspect and analyze forces applied to the chassis. In addition, detailed analysis on sensor data was conducted to compute the maximum and minimum forces on each part of the chassis. The results show that the maximum force of -342.5 KN was applied to the back-bar of the lower A-frame on the back of the car. Table 1 presents loads applied to the chassis in one of the load cases.

Table 1. Chassis loads in one of the load cases

	Front/ Back of Car	Upper/ Lower A-frame	Front/Back bar of A-frame	Max Load (KN)	Min Load (KN)
1	Front	Upper	Front	-40.2	-33.6
2	Front	Upper	Back	-22.8	-8.8
3	Front	Lower	Front	-76.8	-47.2
4	Back	Lower	Back	-342.5	-124.7
5	Back	Tie Rod	-	-35.4	5.6
6	Back	Shock Strut	-	-67.2	-5.0
7	Back	Upper	Front	-13.1	14.7
8	Back	Upper	Back	-50.6	-27.5
9	Back	Lower	Front	-8.1	0.9
10	Front	Lower	Back	24.3	48.4
11	Front	Steering Arm	-	-19.1	-17.3
12	Shock	Shock Strut	-	-21.4	-12.4

These loads and the geometry of ports were used to define the design problem (Figure 8). Some loads and geometries were combined in order to simplify the problem definition.

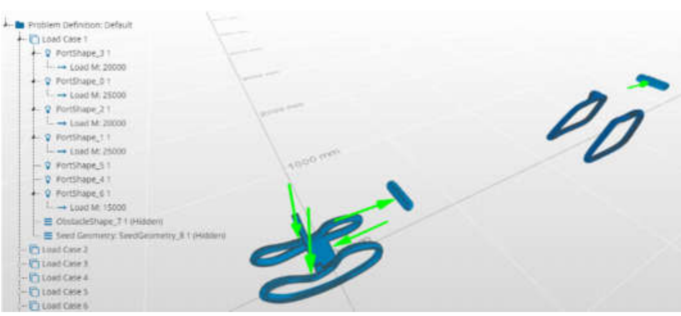

Figure 8. Problem definition

Ensemble Synthesis Methods

Here we demonstrate the results of our synthesis method. The intermediate stages of synthesis and final selected design are shown in Figure 9 and 10. This final design reduced the weight of the initial design from 390 lbs down to 282 lbs.

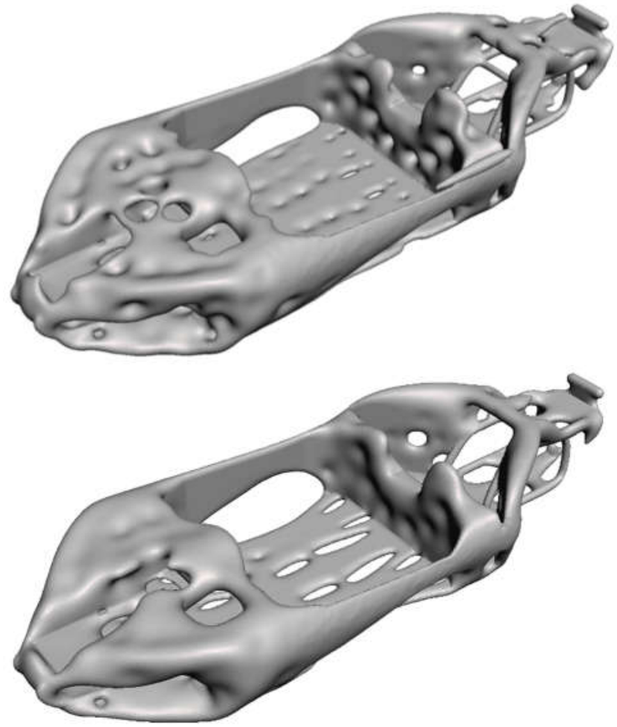

Figure 9. Results of the topology optimization for n=52 and n=99

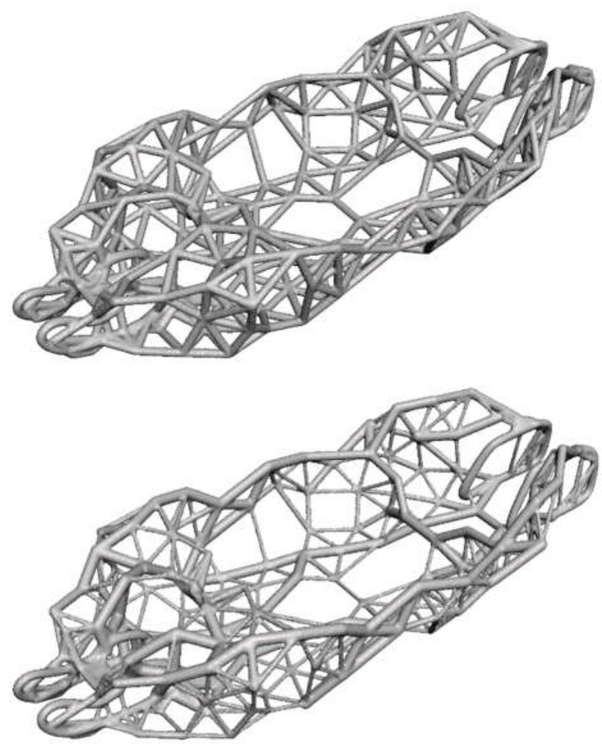

Figure 10. Beam optimization results for selected design. Top: Initial beam network (320lbs). Bottom: Final optimized beam network (282lbs)

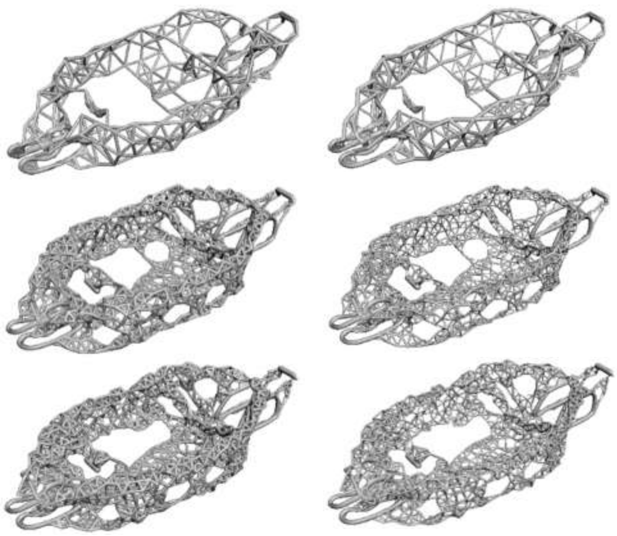

Figure 11. Alternative Beam densities. Top to bottom, increasing beam node densities explored. Left three are initial beam network and right three are optimized beam network.

Figure 9 shows the results of the topology optimization acting on the problem definition at two different iterations. Figure 10 shows the initialized beam network that was created from the output volume and the final thickness optimized beam network that we selected to be fabricated. Figure 11 shows a subset of initial pre-optimized beam networks along with the corresponding optimized beam networks constructed with varying density ϵ illustrating the variety of potential designs that are possible with our system.

Manufacture of Improved Design

The results returned from the testing session in the desert are somewhat dependent on the initial design frame used in the session. This condition arises from the weight and composition of the initial design affecting the loads gathered from the strain gauges. The results that are returned are valid for a baseline design synthesis routine that must be iterated on to progressively deliver more refined results. As such, the intent is to manufacture the synthesized design in the material specified using additive manufacturing methods to accommodate the complex geometry produced through design synthesis. The decision was made to print at 1/3rd scale the chassis using the fused-deposition method in polycarbonate. The model was used for inspection by the design team to determine potential challenges in full-scale manufacture and assembly for the improved chassis design.

DISCUSSION

As methods of design synthesis mature to support the considerable affordances offered by additive manufacturing and availability of computational power progressively increases, the challenge of creating successful designs mutates from the heuristic, iterative expression of design solutions to the efficient and effective representation of the design problem.

In a common design workflow, the information gathered from experimental testing and field data is normally used by engineers to determine appropriate modifications to a design's specifications. Even with large amounts of gathered statistical information and expertise to correlate it to design specifications, the chance for a design to satisfy its overall requirements over the lifetime of an entire product line is very faint, given potentially large changes that over time affect business opportunities, market conditions, global competition, technical advancements. As the rate of progress on additive manufacturing technologies increases, these changes become so rapid, they can even affect a single, full design cycle.

For these reasons, having the ability to effectively represent a design's performance systematically throughout its projected life cycle and directly informing modifications by adjusting its fundamental requirements over time from data gathered in the field becomes a key success factor.

In our project, we demonstrated how data gathered can be used not only for the purpose of generating statistical information, but also to programmatically and directly inform refinement and extensions of a product lifecycle and to improve the correlation between analysis models and real performance metrics. The ensemble shape optimization method used to perform the synthesis of the required design provided enough flexibility to generate structures that have appropriate performance specifications, in a workflow that can rapidly react to critical new information available. The results clearly demonstrate the potential for reducing overall design and maintenance effort (resources, energy, time) by tailoring designs to fit their fundamental requirements and therefore rapid design iterations and improvements to respond to changing business and technical landscape become possible.

LESSONS LEARNED

Lessons Learned from Sensor Data Acquisition

One of the major challenges in collecting sensor data is the consistency of sensor data. These inconsistencies decrease the quality of analysis and require significant time to be resolved. Three major inconsistencies in this study are as follows.

- Consistency in units of measure: All sensors that with a same type should have a same unit of measure. For instance, all thermostats should measure the temperature either in Fahrenheit or Celsius.
- Consistency in orientation of sensors: all orientation-dependent sensors (e.g., accelerometer) should be placed in such a way that the x, y, and z of all of them are in a same direction.
- Consistency in time-logging: the time-logging of all sensors should be consistent so that we can easily reconcile various sensor measures.

Lessons Learned from Design Synthesis

We encountered two main challenges in the process of design synthesis: integration of general data sources into direct design requirements, and selection of an appropriate synthesis method to satisfy the requirements.

Integrating multiple data sources in a prototype design synthesis system is challenging, and reformulating the gathered data to fit the system's problem definition model required several manual processes. The data acquisition and preparation processes required manual intervention by a domain expert to translate critical information into mechanical conditions. Subsequently, our design requirements model allowed us to define equivalent conditions to express the data gathered from the sensors in the form of individual boundary conditions, which the design synthesis system was instructed to satisfy.

While design optimization is a relatively mature field and is a regularly adopted practice in engineering, synthesis of complete mechanical assemblies that provide solutions to complex design requirements is still a developing field. Considering the virtually unlimited design space afforded by new materials and new additive manufacturing techniques, the challenge of adopting synthesis strategies that reflect the numerous characteristics and constraints that emerge from available choices of manufacturing processes is still present. In our work, we considered and experimented with several synthesis and optimization methods to balance the overall goals of achieving the required design performance and manufacturability criteria.

Lessons learned from the Manufacture of Improved Design

The manufacture of the improved design posed significant challenges to the team both in adapting the design problem definition for synthesis and post-processing of the improved design model in order to comply with constraints for various methods of manufacture. Through inspection of the prototype scale-model chassis issues were recognized in accounting for the various tooling required to install components to the full-scale chassis such as modeling obstacles for torque wrenches. Manufacturability constraints built into the synthesis method would eliminate considerable post-processing required to prepare the model for production with additive metal machines.

CONCLUSION

Through this car chassis study we developed a workflow for utilizing sensor data collected from controlled trials on the initial design of the chassis in our new synthesis method. This workflow involves instrumenting the initial design and collecting data from trials representing extreme cases of typical use. The design shape is captured as a high-resolution digital model using laser scanning methods. Then this model is processed to create mesh geometry used as 'ports' or 'obstacles' representing boundary conditions and excluded design regions respectively. The sensor data are then processed for input into Dreamcatcher, the design synthesis tool utilizing an ensemble of structural optimization methods to improve the initial design. The next stage of the workflow involves selecting the improved design for fabrication, followed by inspection, and validation. Finally, the design feedback loop is completed by feeding this design back into the beginning of the workflow. Currently, one loop through the method proposed has been completed. While in this experiment the gathered data are used solely to influence the design synthesis boundary conditions, our method affords alterations of other design requirements such as the location of 'obstacles' between iterations.

One of the main contributions of this study is to present a methodology that combines a data-augmented workflow and ensemble synthesis methods. This method closes the loop between the use and design of products and it can be used in multiple generations of product design. The results of the design synthesis workflow described show that the design is considerably improved over the baseline design weight of 390 lbs. In addition to the quantitative improvements, the systematic instrumentation of product designs can provide very valuable insight to understand a more directly a design's behavior and compare it to its original specifications.

The limitations of our experiments are mainly due to the relatively limited selection of parameters and performance criteria, such as the range of available materials, manufacturing processes and analysis methods for the material structural response, we could directly leverage in the synthesis and optimization processes. In order to fully exploit our system and perform more iterations of the design synthesis loop, several improvements are required that further streamline the processes of data acquisition and performance analysis, and further refinements to the overall design requirements model are necessary to emerge all the available information present in the data. Additionally, the data captured and processed as a representation of our usage scenarios is limited in scope compared to a full product lifecycle, which involves collection and processing of much larger amounts of information.

We expect to improve on this work on multiple fronts. Firstly, we intend to fabricate the full-scale car chassis using additive manufacturing technologies and subsequently instrument it, therefore completing the second iteration of the design loop and proceed to synthesize a second generation design. Additional performance criteria emerging from engineering requirements such as natural frequency and fatigue will then be introduced in the synthesis and multi-objective optimization process. Furthermore, we intend to establish an automated process for the import of raw sensor data feeds and direct translation into design requirements and association with boundary conditions will be implemented, based on the detailed study of the required processes that emerged from this work. The data available from the sensors mounted in the driver helmet and gloves can also be considered as a source of correlation between chassis/suspension behavior and driver reaction, forming a metric of overall vehicle response that can influence both the chassis construction and the vehicle setup. Finally, we intend to acquire and process considerably larger datasets that correspond to a wider spectrum of usage scenarios, to more faithfully represent the typical lifecycle of a more mass-produced design.

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