Interactive Design of Animated Plushies

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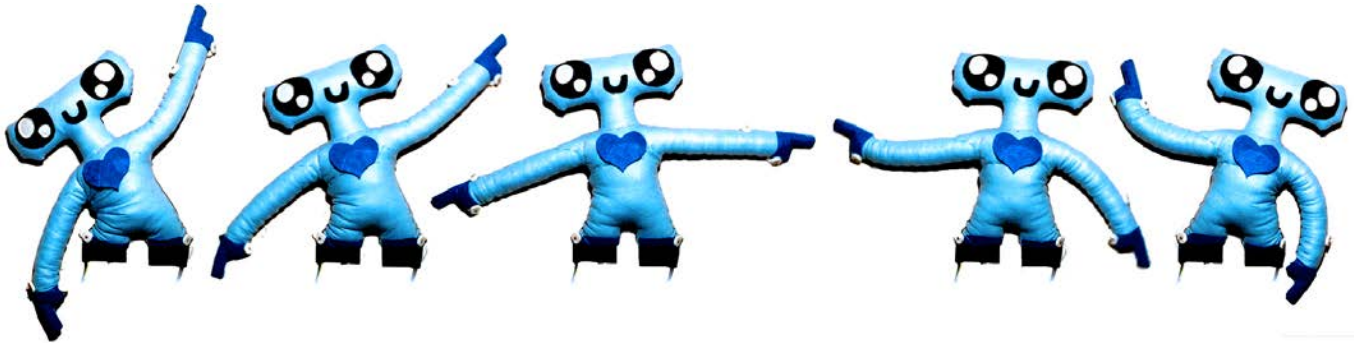

Fig. 1. An animated plushie designed and fabricated using our computational approach. Tendons run through the plushie's skin, and are contracted by motorized winches inside of the plushie's body.

We present a computational approach to creating animated plushies, soft robotic plush toys specifically-designed to reenact user-authored motions. Our design process is inspired by muscular hydrostat structures, which drive highly versatile motions in many biological systems. We begin by instrumenting simulated plush toys with a large number of small, independently-actuated, virtual muscle-fibers. Through an intuitive posing interface, users then begin animating their plushie. A novel numerical solver, reminiscent of inverse-kinematics, computes optimal contractions for each muscle-fiber such that the soft body of the plushie deforms to best match user input. By analyzing the co-activation patterns of the fibers that contribute most to the plushie's motions, our design system generates physically-realizable winch-tendon networks. Winch-tendon networks model the motorized cable-driven actuation mechanisms that drive the motions of our real-life plush toy prototypes. We demonstrate the effectiveness of our computational approach by co-designing motions and actuation systems for a variety of physically-simulated and fabricated plushies.

CCS Concepts: • **Computing methodologies** → **Physical simulation**; • **Computer systems organization** → *Robotic control*;

Additional Key Words and Phrases: animation, plushies, computational design, soft robotics

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1 INTRODUCTION

Endeared companions to children and adults alike, plush toys have enjoyed widespread popularity since their commercial debut in the late 1800's. Thanks to the relative ease with which they are made, a Do-It-Yourself movement for plush toys emerged shortly thereafter and continues to flourish today. Recognizing an interesting technical challenge, the research community has taken an interest in formalizing computational design methods that facilitate the creation of plush toys [Igarashi and Igarashi 2008; Mori and Igarashi 2007] and other related structures made by adjoining flat patterns [Furuta et al. 2010; Skouras et al. 2014]. The solutions proposed to date help non-experts create designs that depict *static* shapes. In contrast, our goal is to make equally accessible the creation of plush toys that are specifically-designed to produce compelling motions.

To create animated plush toys, it is common practice to enclose traditional robotic devices in fabric exteriors. While great from the point of view of motion capabilities, this approach has two important drawbacks. First, the rigid nature of the embedded electromechanical assemblies hinders the large, organic deformations that are expected during typical interactions. Second, designing and fabricating the internal mechanisms can be very difficult, and therefore largely inaccessible to casual users. An alternative strategy, which we adopt for our work, is to employ cable-driven setups. In this setting, motions are created by activating, through pulling or contractions, cables that are laid out within the soft body of the plush toys. Ensuring that the resulting motions are desirable, however, requires solving a challenging design problem: the number of cables to be used, their routing, the patterns of co-activation, and the physical interactions between the tensioned cables and the plush toy are all coupled and must be considered concurrently.

Overview and contributions. We propose a computational approach to interactively designing cable-actuated robotic plush toys.

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Functionality-aware Retargeting of Mechanisms to 3D Shapes

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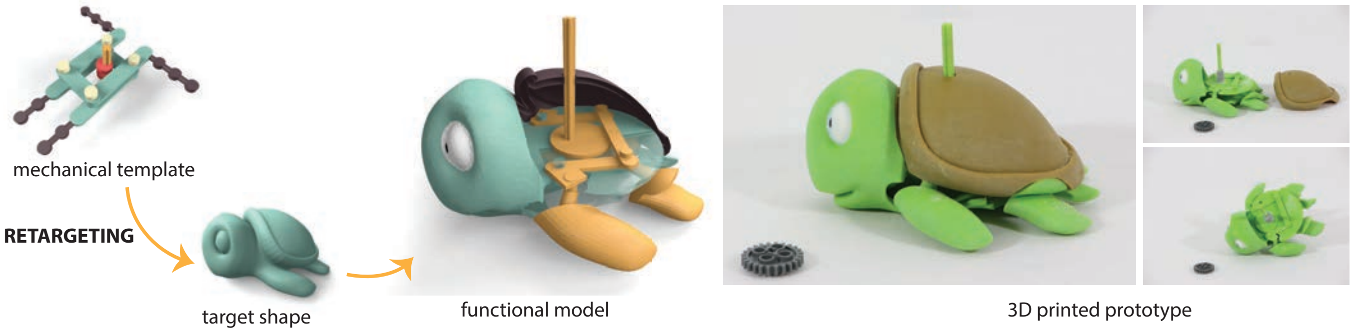

Fig. 1. Our interactive design system allows users to retarget a given mechanical template (top left) to an input shape (bottom left). Our optimization-in-the-loop approach generates a functional model (center) that can be 3D printed (right).

We present an interactive design system to create functional mechanical objects. Our computational approach allows novice users to retarget an existing mechanical template to a user-specified input shape. Our proposed representation for a mechanical template encodes a parameterized mechanism, mechanical constraints that ensure a physically valid configuration, spatial relationships of mechanical parts to the user-provided shape, and functional constraints that specify an intended functionality. We provide an intuitive interface and optimization-in-the-loop approach for finding a valid configuration of the mechanism and the shape to ensure that higher-level functional goals are met. Our algorithm interactively optimizes the mechanism while the user manipulates the placement of mechanical components and the shape. Our system allows users to efficiently explore various design choices and to synthesize customized mechanical objects that can be fabricated with rapid prototyping technologies. We demonstrate the efficacy of our approach by retargeting various mechanical templates to different shapes and fabricating the resulting functional mechanical objects.

CCS Concepts: • **Computing methodologies** → **Graphics systems and interfaces**; *Shape modeling*; • **Applied computing** → *Computer-aided manufacturing*;

Additional Key Words and Phrases: Fabrication, Functional structure, Mechanical structure

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1 INTRODUCTION

The increasing accessiblity of rapid manufacturing devices and 3D printing services has made it possible for more and more users to fabricate a variety of functional objects. In recent years, many compelling examples have emerged from the maker community, including animated characters, mechanical automata, and simple robots. However, despite steady advances in computer-aided digital modeling tools, designing such functional objects is still very challenging and typically reserved for experts. Developing design tools that facilitate this task and make it accessible to a wider audience is an open research challenge at the intersection of computational fabrication and computer graphics.

The goal of our work is to address this problem for functional objects that are based on simple mechanisms, such as an assembly of gears and gear trains, cams, or linkages. Functional mechanical objects can be defined by a few high-level properties: *form*, which represents the shape and appearance of the design; *mechanical architecture*, which describes the configuration of mechanical parts; and finally, the *function* resulting from the combination of form and mechanical architecture. A challenge in designing such objects with conventional tools is that the user must develop the form and mechanism *concurrently*. This requires expertise both in shape modeling and mechanical engineering. For example, to design a given functional object, a typical workflow usually requires modeling an appropriate mechanism, shaping the form of the object, connecting

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A Computational Design Tool for Compliant Mechanisms

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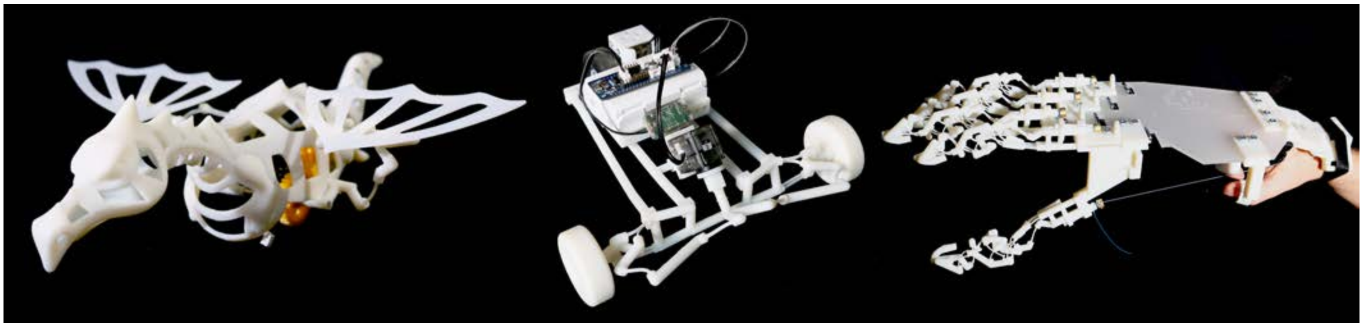

Fig. 1. Our computational tool for designing compliant mechanisms allows non-expert users to generate compliant versions of conventional, rigidly-articulated mechanisms. As we demonstrate with a diverse set of examples ranging from a spatial wing (left) and steering mechanism (middle) to a compliant hand well-suited for teleoperation tasks (right), our technique leads to structurally-sound and function-preserving compliant designs.

We present a computational tool for designing compliant mechanisms. Our method takes as input a conventional, rigidly-articulated mechanism defining the topology of the compliant design. This input can be both planar or spatial, and we support a number of common joint types which, whenever possible, are automatically replaced with parameterized flexures. As the technical core of our approach, we describe a number of objectives that shape the design space in a meaningful way, including trajectory matching, collision avoidance, lateral stability, resilience to failure, and minimizing motor torque. Optimal designs in this space are obtained as solutions to an equilibrium-constrained minimization problem that we solve using a variant of sensitivity analysis. We demonstrate our method on a set of examples that range from simple four-bar linkages to full-fledged animatronics, and verify the feasibility of our designs by manufacturing physical prototypes.

CCS Concepts: • **Computer graphics → Computational geometry and object modeling**; *Physically based modeling*;

Additional Key Words and Phrases: Compliant Mechanism Design, Computational Design, 3D Printing

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1 INTRODUCTION

Engineers routinely design for strength and stiffness. Steel and concrete prevent deflections in buildings, and machines resort to rigid articulation in order to avoid deformations. But although most human designs are inspired by Nature, rigidity is a concept foreign to the living world: from a kangaroo's legs to the wings of a bat—bones, tendons, and cartilage are the nuts and bolts of organic machines, and deformation is an integral part of the design, crucial for both efficiency and robustness. Unfortunately, designing for flexibility requires deep understanding and precise predictions of finite deformations, which proves to be substantially more difficult than relying on rigidity.

Fueled by progress in technology and computation, however, many fields of engineering have started to *embrace deformation* and to leverage flexibility for better, more elegant, and ultimately more satisfying designs. Applied to machines, this turn to the flexible leads to *compliant mechanisms*, i.e., mechanical devices that perform motion not through rigid articulation but by virtue of elastically deforming flexures. Compliant mechanisms enjoy widespread use in industry, where they are valued for their accuracy, ease of manufacturing, scalability, and cost efficiency. The spectrum ranges from specialized microelectromechanical systems (MEMS) for miniature sensors and actuators [Kota et al. 2001], to more mundane devices including monolithic pliers and wiper blades, and to commonplace products such as binder clips, backpack latches, and shampoo lids.

We are primarily interested in exploring the potential of compliant mechanisms for personalized automata and animatronics. With the ability to create complex geometry and its repertoire of flexible, plastic-like materials, 3D printing is an ideal way of manufacturing

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Computational Design of Telescoping Structures

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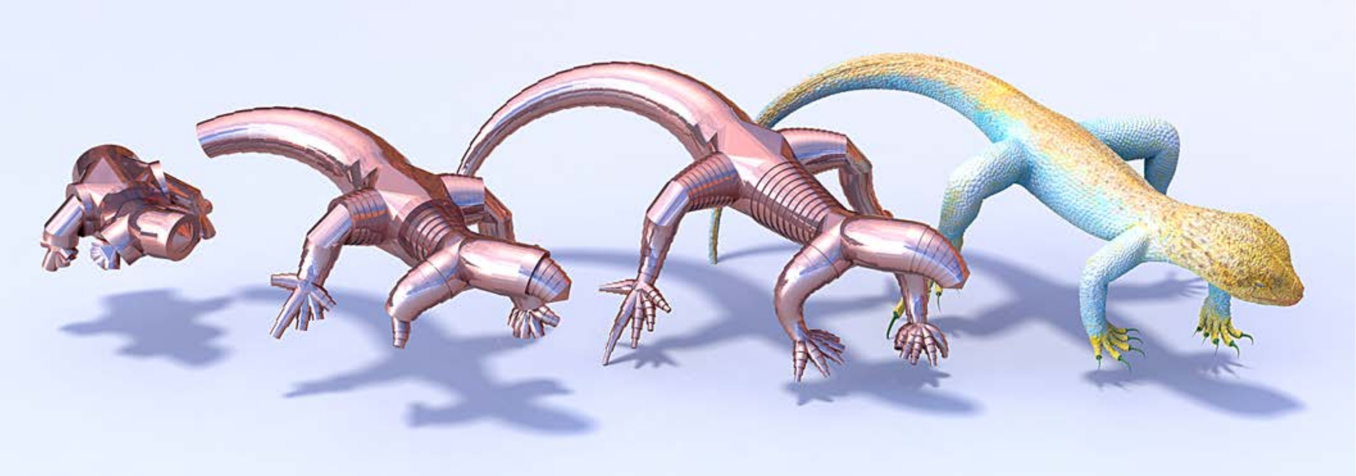

Fig. 1. A telescoping lizard in various stages of extension approximates an input surface (right). We parameterize telescoping structures as networks of smooth space curves with special geometric properties, allowing users to rapidly explore the space of telescoping designs.

Telescoping structures are valuable for a variety of applications where mechanisms must be compact in size and yet easily deployed. So far, however, there has been no systematic study of the types of shapes that can be modeled by telescoping structures, nor practical tools for telescopic design. We present a novel geometric characterization of telescoping curves, and explore how free-form surfaces can be approximated by networks of such curves. In particular we consider piecewise helical space curves with torsional impulses, which significantly generalize the linear telescopes found in typical engineering designs. Based on this principle we develop a system for computational design and fabrication which allows users to explore the space of telescoping structures; inputs to our system include user sketches or arbitrary meshes, which are then converted to a curve skeleton. We prototype applications in animation, fabrication, and robotics, using our system to design a variety of both simulated and fabricated examples.

CCS Concepts: • **Computing methodologies → Parametric curve and surface models**; • **Applied computing** → Computer-aided design;

Additional Key Words and Phrases: telescoping structures, deployable structures, computational design, fabrication, discrete differential geometry

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1 INTRODUCTION

A pirate's telescope, consisting of straight, nested cylinders, is a familiar sight commonly associated with tales of seafarers and explorers. The simple telescoping mechanism behind these so-called *spyglasses* has endured over the centuries, owing to its simple effectiveness for compact storage and rapid deployment, and is still widely used in modern engineering (Garrette and Ryan 1969; McCord and Williford 1966). Deployable structures have more broadly become important in applications where an unwieldy object must be stored in or transported through a smaller vessel, *e.g.*, large solar panels carried by space-bound vessels (Stinson 2014), or arterial stents that must travel through narrow passages during surgery (Kuribayashi et al. 2006). Generalized telescoping mechanisms likewise hold great promise for deployable design, providing a fundamentally new kind of joint that can be reshaped in surprising and entertaining ways. The design space of telescoping structures, however, remains relatively unexplored. This paper is a first foray into mathematical and computational models for generalized telescopes and their applications.

At the most basic level, a *telescoping structure* consists of a sequence of nested units that can be extended and retracted. Most modern instances of such structures consist of a linear sequence of

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Dynamics-Aware Numerical Coarsening for Fabrication Design

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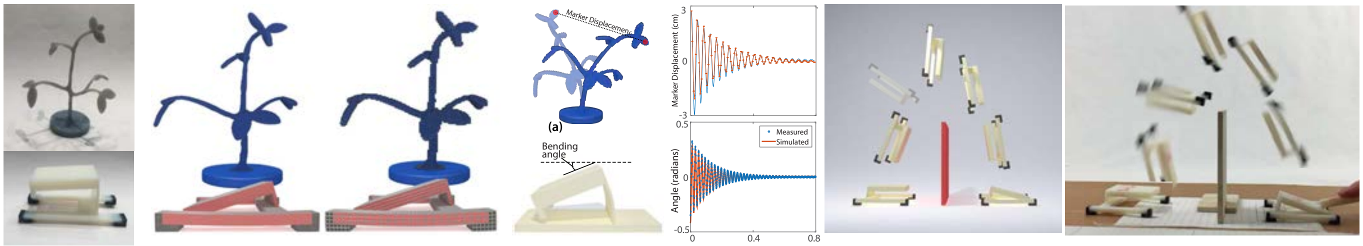

(a) Model (b) Coarsening (c) Measurement (d) Simulation (e) Fabrication

Fig. 1. We introduce measurement-based, dynamics-aware coarsening (DAC) and the Boundary Balanced Impact (BBI) model - accelerating the simulation of dynamic elastica to obtain predictive *and* efficient accuracy required for fabrication-design iterations, testing and validation. We begin with initial models and real world fabricated materials (a). We then apply dynamics-aware, measurement-based coarsening (DAC) (b and c). The DAC model with BBI then simulates a range of designs that match the real-world dynamic behaviors of corresponding 3D-printed objects undergoing large-deformation loading, frictional contact and high-speed, transient dynamics with impact (e).

The realistic simulation of highly-dynamic elastic objects is important for a broad range of applications in computer graphics, engineering and computational fabrication. However, whether simulating flipping toys, jumping robots, prosthetics or quickly moving creatures, performing such simulations in the presence of contact, impact and friction is both time consuming and inaccurate. In this paper we present Dynamics-Aware Coarsening (DAC) and the Boundary Balanced Impact (BBI) model which allow for the accurate simulation of dynamic, elastic objects undergoing both large scale deformation and frictional contact, at rates up to 79 times faster than state-of-the-art methods. DAC and BBI produce simulations that are accurate and fast enough to be used (for the first time) for the computational design of 3D-printable compliant dynamic mechanisms. Thus we demonstrate the efficacy of DAC and BBI by designing and fabricating mechanisms which flip, throw and jump over and onto obstacles as requested.

CCS Concepts: • **Computing methodologies → Physical simulation**;

Additional Key Words and Phrases: Numerical Coarsening, Fabrication, Deformation, Dynamics, Contact-Impact

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1 INTRODUCTION

We present a pair of new methods to accurately simulate geometric and material nonlinearities subject to frictional contact, large loads and high-speed collisions at rates significantly more than an order-of-magnitude faster than previously available. Our methods combine efficiency and accuracy to enable design-for-fabrication optimization. They can be used for both fast, realistic animation and engineering analysis.

Advances in computational design, physical modeling and rapid manufacturing have enabled the fabrication of objects with customized physical properties. In computer graphics these extend from stable standing and spinning [Bächer et al. 2014; Prévost et al. 2013] to mechanism design [Coros et al. 2013; Thomaszewski et al. 2014] and deformable character manufacture [Bickel et al. 2012; Skouras et al. 2013], to name just a few. Computational design in the presence of high-speeds, large deformation, frictional contact and impact, however, remains largely unaddressed.

Here we look towards a new generation of efficient mechanisms for practical *dynamic* function [Lipson 2014; Reis 2015; Reis et al. 2015; Rus and Tolley 2015]. In order to extend physics-driven computational design to this domain, however, a bottleneck must be overcome - the physical simulation itself. Simulations must accurately replicate the behavior of elastic materials subject to high-speed, transient dynamics. Modeling these systems combines many of the remaining grand challenges in simulating elastica. Specifically we must accurately resolve nonlinear elasticity, large deformations, stiff materials, high-speed dynamics, rapid loading and unloading, frictional contact, internal friction, high-speed collisions, and rebound.

State-of-the-art FEM systems currently able to accurately match these effects are exceedingly expensive - runtimes on the order of days are standard to perform a single simulation in many cases [Belytschko et al. 2013]. Thus, while generating a single simulation for

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Holographic Near-Eye Displays for Virtual and Augmented Reality

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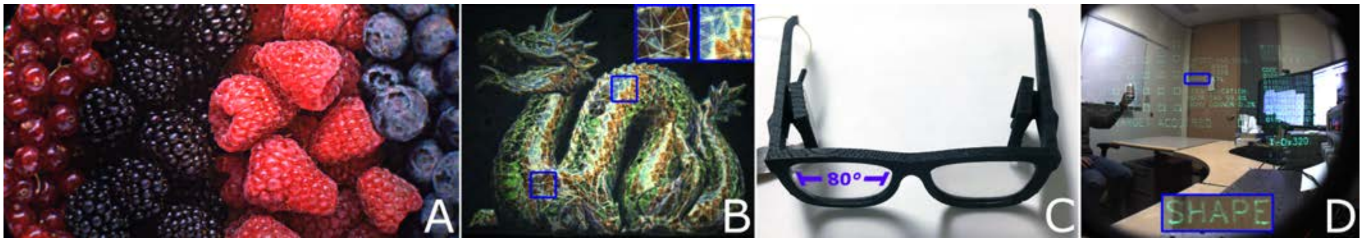

Fig. 1. *A)* Photograph of prototype holographic near-eye display presenting a full color image. *B)* Photograph of prototype displaying a true 3D hologram; each point of the 3D model appears at an individually addressable focal depth. Blue bordered inset regions show in-focus chest and out-of-focus tail. *C)* Photograph of prototype display in an eyeglasses-like form factor with a horizontal field of view of 80° (driving electronics external). *D)* Photograph of prototype in *C)* displaying an augmented image. Blue bordered inset region shows magnification of 1 pixel line width text. Berries image by Ana Blazic Pavlovic/Shutterstock. Dragon model by Stanford Computer Graphics Laboratory.

We present novel designs for virtual and augmented reality near-eye displays based on phase-only holographic projection. Our approach is built on the principles of Fresnel holography and double phase amplitude encoding with additional hardware, phase correction factors, and spatial light modulator encodings to achieve full color, high contrast and low noise holograms with high resolution and true per-pixel focal control. We provide a GPU-accelerated implementation of all holographic computation that integrates with the standard graphics pipeline and enables real-time (≥90 Hz) calculation directly or through eye tracked approximations. A unified focus, aberration correction, and vision correction model, along with a user calibration process, accounts for any optical defects between the light source and retina. We use this optical correction ability not only to fix minor aberrations but to enable truly compact, eyeglasses-like displays with wide fields of view (80°) that would be inaccessible through conventional means. All functionality is evaluated across a series of hardware prototypes; we discuss remaining challenges to incorporate all features into a single device.

CCS Concepts: • **Hardware** → *Displays and imagers*;

Additional Key Words and Phrases: holography, near-eye display, augmented reality, virtual reality, computational displays

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1 INTRODUCTION

It's an exciting time for near-eye displays. In the previous year, a new crop head mounted displays (Oculus Rift and HTC VIVE) have demonstrated sufficient resolution, tracking performance, and latency to begin to offer compelling virtual reality (VR) experiences to consumers. In the same year, the Microsoft HoloLens has demonstrated these same characteristics for the first time in a self-contained augmented reality (AR) device.

There's still a lot of work to be done. The lightweight optics found in current virtual reality near-eye displays do not scale to provide resolution on par with human visual acuity. Achieving such performance with conventional optics would require complex, multi-element optics with impractical size, cost and weight. Custom prescription lenses are required to correct visual impairments. Likewise, current optical solutions do not provide a path to obtain wide field of view (FOV) and high resolution see-through augmented reality displays in eyeglasses-like form factors that would enable true mobility and all-day use. We have also not encountered practical solutions to incorporate true 3D, multi-focal depth cues in these devices to eliminate the accommodation-convergence conflict and mimic the fidelity of our natural vision.

Solutions to these challenges require precise control of the wavefront of light. It would be very difficult to overcome all of these challenges in a passive optical device. We turn to *computational* solutions, in which the hardware is simplified and the complexity of wavefront control is pushed into software. One potential solution is *light field* displays, in which wavefront control is expressed through individually addressable ray bundles. Some impressive results have been achieved to date [Huang et al. 2015; Lanman and Luebke 2013]. However, light field displays have a few limitations. Ray bundles inefficiently encode wavefronts, allowing only coarse approximation of wavefront shape through sparse samples and causing high resolution loss. Due to diffraction, the selected size of the ray bundles also dictates a fundamental trade-off between the maximum

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