Title

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Manipulating OAM Beams for Torque and Dynometric Systems

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Abstract:
This review investigates adaptable orbital-angular-momentum beams for developing a reliable ultra-fast dynamometer torque monitor for real motor systems, highlighting recent structured-light architectures that enable Doppler momentum analysis via programmable phase manipulation.

INTRODUCTION
The field of photonics and structured light is a rapidly emerging discipline with widespread applications. The control of amplitude, phase, and polarization at the wavelength scale has enabled progress in optical communication, trapping, and advanced imaging. By manipulating these spatiotemporal variant field vectors and their amplitude and phase distributions, researchers have developed optical phenomena, such as orbital and spin angular momentum (OAM) beams, that can support many advanced applications. A key feature of OAMs is the rotational Doppler effect, which can detect a frequency shift in an emitted beamline caused by light scattering from a rotating body. The proposed frequency shift is then proportional to an object's angular velocity and OAM charge ℓ [2], allowing these field vectors to act as an optoelectronic system that can detect torque, velocity, and rotational inertia from the returned light signal.

The study, *Integrated Structured Light Architectures* [1], corroborates the beamline principle by introducing a new laser architecture that generates programmable light structures, including vortex and OAM beams. The OAM beams have the potential to motivate further research on mechanical sensors by serving as a dynamometer to monitor the velocity and torque of mechanical rotors.

These principles have a specific application in the automotive industry. At UCLA, the Bruin Racing Baja team builds a gas-powered high-torque off-roading vehicle for a national competition. Under strict SAE (Society of Automotive Engineers) guidelines, no team is allowed to modify the engine; instead, to maximize power, UCLA implements an electrically controlled continuous variable transmission (ECVT) and actuator system with a mechanical dynamometer for static testing. Due to its size and interference with the car, the dynamometer is limited to static use, preventing live data collection during competitions and off-road drives. An optoelectronic dynamometric system mitigates this by being non-invasive, lightweight, and vibration-resistant.

Ultimately, this paper focuses on the application of OAM to a torque dynamometer developed for the Bruin Racing Baja car. Due to the optical nature of the field, the OAM can be defined as a Laguerre-Gaussian model (LG_0^{ℓ}) [2] with radial index p = 0, topological charge ℓ, and electric field at the axial position

$$E(r, \theta, z) \propto r^{|\ell|} exp(-r^2/(w(z)^2)) exp(i\ell\theta) exp(ikz). \tag{1}$$

When an electric field is applied to the car's drivetrain, the rotating surface scatters light due to the helical phase of the OAM beams [5]. The proportionality of this shift to angular velocity and topological charge will form the physical basis for torque extraction. This paper will focus on the rotational Doppler shift produced by a motor with angular velocity Ω, analyzing the frequency shift created by the modeled electric field to determine the torque given by the equations below:

$$\Delta f = \ell\Omega/(2\pi) \tag{2}$$

$$\tau = I\Delta\Omega/\Delta t. \tag{3}$$

As the methods discussed in [1] improve, it will be exciting to see whether structured light can provide a more reliable sensing and validation method for mechanical subsystems, enabling new advancements in electro-optical applications.

METHODS

The experimental procedure in [1] demonstrates a system capable of producing controllable, structured beams, such as optical vortices and OAMs, by alternating the phase, intensity, and polarization. The laser used in this procedure uses coherent beam combinations to control the parameters and produce a focused beam, resulting in a complex light beam composed of individually controllable components.

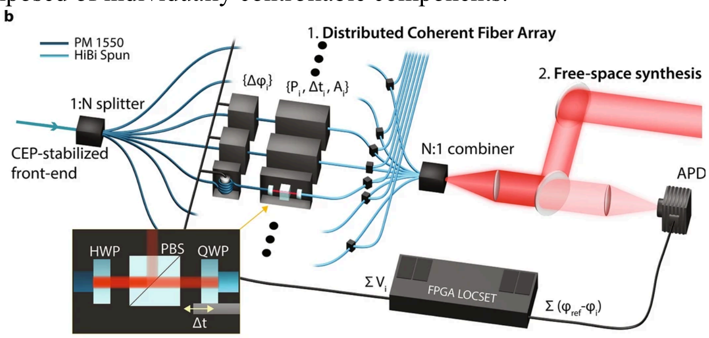


Fig. 1 Experimental Setup (Ref. [1], Fig. 1b).

As shown in Figure 1, the procedure consists of a single incident beam that is split into N beamlines. Each beamline undergoes independent modulation of its phase ($\Delta\phi_i$), polarization state (P_i), timing (Δt_i), and amplitude (A). These independently programmed beams are subsequently recombined to synthesize a desired structured-light field. The source is a femtosecond mode-locked laser centered near 1550 nm in the telecom band. After splitting, all beamlines remain mutually phase-coherent by locking each channel to a reference beam through the FPGA-based LOCSET stabilization system.

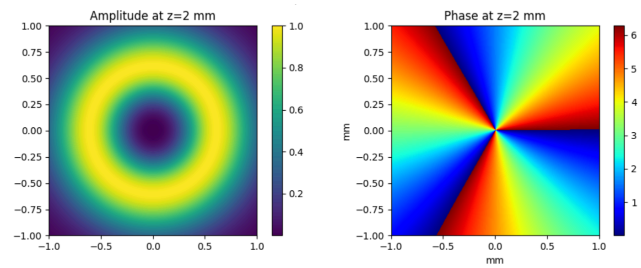
The work *Compact On-Chip Ultrasonic Motor Actuated by Surface-Bounded Sonic OAM* [4] builds on controllable light beams discussed by Lemons et al. (2021) [1] by explaining how OAMs can produce measurable mechanical torque on micro-rotors via surface-bound OAM modes. Their findings demonstrate the ability to convert linear motion from a single source into surface-bound OAM with high efficiency in a contactless manner. This provides the physical basis for this report's use of OAM in torque-sensing systems.

For the Baja application, the optical system must operate reliably in a rugged, off-road environment. Mechanical vibrations and chassis-induced misalignment pose challenges for maintaining beam overlap and phase coherence. By using a self-calibrating reference beam, as described in [1], the system retains consistent phase locking and coherent combination, thereby minimizing vibrational noise and mitigating these issues. Weight constraints also motivate the use of compact optical components, potentially implemented through MEMS-based steering and miniaturized rugged enclosures to reduce sensitivity to vibration [6].

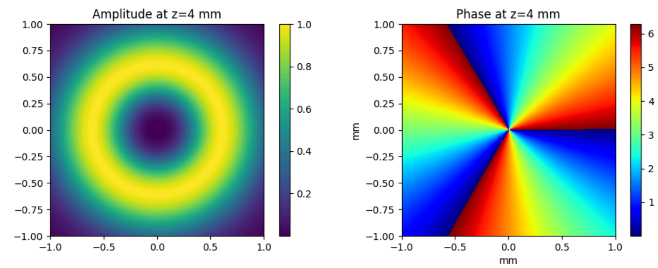
For torque detection, a higher-order OAM beam with topological charge $\ell = 3$ can be generated using programmable spatial light modulators [3]. The returning beam carries rotational Doppler information induced by the motor shaft. Fast photodetectors, combined with FPGA-based phase analysis and interferometric detection, can monitor the angular displacement and Doppler-induced frequency shifts. This requires a Femtosecond mode-locked laser at 1550nm, a beam splitter, coherent-combination optics, a detection path, and an FPGA-based analysis unit.

The measured Doppler frequency shift provides a proportional indicator to the rotational speed of the motor, where the relationship $\Delta f = \ell\Omega/2\pi$ (2) holds for torque ($\tau = I\Omega/\Delta t$) (3). Further modeling the electric field in (1), the experimental setup provides quantitative evidence of the relationship between OAM-enabled phase changes produced by the rotational Doppler shift retrieved from the torque of the Baja motor.

RESULTS AND INTERPRETATION



(a) (b)

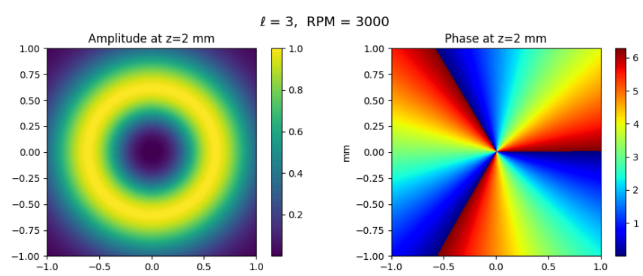


(c) (d)

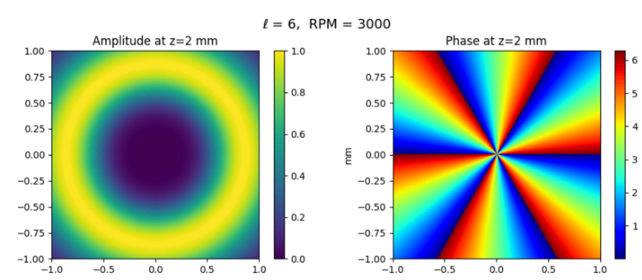
Fig. 2 Near-field amplitude [a] and phase combination [b] change of z = 2mm, and amplitude [c] and phase combination [d] of z = 4mm.

The synthesized results demonstrate the ability to generate OAM beams with controllable topological charges and distance z using a programmable FPGA. The plots in Fig. 2 corroborate Lemons et al. (2021) [1] in showing the circular intensity profile that produces a central null surrounded by a bright annular ring, which is characteristic of a Laguerre–Gaussian OAM mode with topological charge $\ell > 0$ [5]. The vanishing intensity at the center corresponds to the phase singularity of the vortex, where the optical phase is undefined. Because the ring radius remains nearly constant between z = 2 mm and z = 4 mm, the beam exhibits stable propagation with minimal divergence over short distances. This indicates that the OAM mode maintains structural integrity even in a dynamic environment, supporting its suitability for Baja's fast-paced torque-sensing system.

The corresponding phase maps show a continuous azimuthal phase ramp from 0 to 2π, wrapping around the central singularity. This confirms the helical phase structure expected for OAM beams, with each full 2π rotation corresponding to one unit of topological charge ℓ. Together, the amplitude and phase distributions verify the presence of orbital angular momentum and motivate further experimentation with higher-order modes, characterized by increased phase windings, to enhance sensitivity and maximize measurable torque.



(a) (b)



(c) (d)

Fig. 3 Near-field amplitude [a] and phase combination [b] of change in topological charge ℓ = 3, and amplitude [c] and phase combination [d] of ℓ = 6.

The Baja car has an RPM range of 1800-3800, with an average of 3000 RPM, which can be used to model the OAM amplitude and phases by varying ℓ to determine which helical axis provides the best outputs for the solution. Let's first compute the average Ω value for the Baja car, where $\Omega = 2\pi(RPM)/60$.

At RPM=3000, Ω=314.16rad/s, and the rotational Doppler shift becomes $\Delta f = \ell\Omega/2\pi = \ell \cdot 50$ Hz from (eq 2). Thus, for ℓ = 3, Δf = 150Hz, which is well above the noise floor for standard GHz-band photodiodes, resulting in a clean frequency separation to make real-time detection feasible. Fig. 3 confirms this assumption, as ℓ increases, the phase graph shows more color sections, indicating a larger phase difference in the system and faster rotation. It also reveals the system's stability at higher OAM orders. As seen from ℓ = 3 to ℓ = 6, the radius of the dark core increases, due to larger beam footprints, where more phase wraps lead to higher wavefront complexity and greater sensitivity to aberrations and misalignment. Thus, by increasing ℓ, the system tests how much ℓ the system can support. This is seen when setting ℓ ≥ 6, where the edges are cutoff by the box, rendering the system unstable and causing it to diverge faster. Thus, the lens cannot handle increased divergence, and noise will appear, degrading the results. As such, ℓ = 3 validates the assumption of torque detection, as it yields the best results in minimizing distortion and achieving high stability.

CONCLUSION

The research applies structured-light and OAM-beam physics to the development of a compact, robust dynamometer for the Bruin Racing Baja vehicle. By leveraging the rotational Doppler effect and the tunability of programmable OAM beams, this analysis proposes a torque-sensing technique that can operate in high-vibration, harsh outdoor environments without requiring mechanical contact, which would violate SAE motor regulations. Simulations confirm stable OAM propagation and demonstrate ℓ = 3 provides optimal torque sensitivity while maintaining beam integrity. Integrating this system with ruggedized, miniature optical hardware could enable real-time torque and speed monitoring during vehicle operation, a capability that traditional dynamometers cannot provide.

The long-term viability of this system relies critically on phase-locking techniques enabled by FPGA-based LOCSET stabilization. These mechanisms ensure complex light structures, such as OAM beams, compensate for phase drift caused by vibration, thermal fluctuations, or chassis deformation. By actively maintaining mutual coherence across beamlines, the system preserves the accuracy of the rotational Doppler measurement during aggressive driving conditions. As such, the integration of advanced phase-locking architectures represents the next significant step toward deploying OAM-based sensing on fully mobile, real-world automotive subsystems.

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