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ABSTRACT

Acoustic levitation enables contact-free particle manipulation, yet dynamic six-degree-of-freedom (6-DOF) control of non-spherical macroscopic bodies has remained out of reach: rotational and translational dynamics couple non-trivially, and existing demonstrations are restricted to spherical objects or static configurations, or achieve motion by mechanically repositioning the levitator. We demonstrate controlled, stable, and purely field-based 6-DOF manipulation of macroscopic non-spherical rigid bodies on a stationary phased array system, using kinematic feedforward control without any object-specific dynamic model. The architecture combines a Galerkin boundary element model of acoustic radiation forces and torques with our semidefinite programming (SDP) framework for translating optimized pressure fields. Rotational keyframes are obtained offline via nonlinear optimization and stored in a lookup table (LUT) sampling the rotational workspace. SDP then translates the incident pressure field of any LUT entry within the working volume. For a reference trajectory, retrieved keyframes and shifted fields are merged offline into a phase sequence streamed at a 1 ms update rate without re-trapping. Experiments on a wooden cross and stick validate the architecture in the Mie and geometric regimes. Static rotational precision at LUT-sampled poses stays below 0.45° (mean) across all examined axes, with peak deviations up to 2.82° at large angles. Dynamic manipulation at velocities up to 40 mm/s achieves tracking errors below about 3% of the object length. Supplementary material videos show linear and infinity symbol trajectories, continuous 6-DOF maneuvers in a single uninterrupted run, and trajectory composition at non-trivial poses. These results open the route to closed-loop control of macroscopic objects.

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Acoustic levitation¹ suspends and manipulates objects without contact via nonlinear acoustic radiation forces,² trapping solid and liquid samples across diverse material properties,^{3–9} sizes,^{10–15} and masses^{8,9,11} in air,¹³ water,¹⁶ and biological tissue.¹⁷ As a reconfigurable, contamination-free sample holder, it enables applications in photogrammetry,^{18,19} crystallography,²⁰ materials science,⁹ pharmacy,²¹ and spectroscopy.²² While early levitation systems based on Langevin transducers²³ were largely limited to static trapping, the transition to phased arrays of transducers²⁴ (PATs), pioneered by Ochiai *et al.*,²⁵ Hoshi *et al.*,²⁶ and Marzo *et al.*,¹¹ enabled dynamically reconfigurable pressure fields. PATs employ low-power elements with individually controllable phase,¹¹ amplitude,²⁷ or frequency.²⁸ Such PATs create complex acoustic traps—pressure fields that suspend objects in force-torque equilibrium;¹¹ modulation translates and rotates them.

According to the ratio d/λ of the characteristic object dimension d to the acoustic wavelength λ , acoustic manipulation is classified into Rayleigh ($d \ll \lambda$), Mie ($d \approx \lambda$), and geometric ($d \gg \lambda$) regimes. In the Rayleigh regime, PAT-based manipulation in mid-air has advanced through holographic acoustic elements,¹¹ multi-point algorithms,^{27,29,30} and singular value decomposition (SVD),¹⁸ the latter enabling six-degree-of-freedom (6-DOF) control. In contrast, manipulation in the Mie and geometric regimes has largely been confined to static levitation;^{12–14,31} full 6-DOF manipulation of macroscopic objects ($d \geq \lambda$) remains challenging due to the inverse acoustic field problem.

While the forward mapping from transducer phases ϕ to radiation force F_{rad} and torque T_{rad} is uniquely defined, the inverse mapping is ambiguous. Existing approaches^{12–14} rely on computationally

intensive nonlinear optimization that must be repeated for every object pose, limiting them to static levitation. Notably, Inoue *et al.*¹² used the boundary element method (BEM) to suspend macroscopic objects in mid-air by geometry-tailored pressure fields. We recently introduced a semidefinite programming (SDP) framework³² that recasts the inverse problem as phase retrieval solvable in milliseconds. However, the spherical harmonics force model^{13,14} restricted experiments to translating a Mie sphere, leaving rotational DOFs unaddressed. Translational and rotational manipulation of larger-than-wavelength-sized non-spherical bodies was instead demonstrated by Sundblad *et al.*³³ using singular value decomposition (SVD),¹⁸ and by Ezcurdia *et al.*³⁴ who achieved 6-DOF manipulation of elongated Mie-scale parts for contactless assembly by combining field-based reorientation with mechanical repositioning of the levitator by a robot arm. Here, we combine SDP with Galerkin-BEM¹² to demonstrate stable, dynamic 6-DOF manipulation of non-spherical macroscopic rigid bodies using a stationary phased array system. Unlike the SVD-based field synthesis employed by Sundblad *et al.*,³³ which prescribes the pressure and its gradient at manually chosen points and solves a corresponding linear system, our approach optimizes the transducer phases directly for force/torque equilibrium of the body, with local asymptotic stability³⁵ promoted by construction. Crucially, SDP avoids field reoptimization per object pose: BEM is used for the computation of a small set of rotational keyframes, buffered in a lookup table (LUT) that samples the rotational workspace, while SDP generates the translations of the incident pressure field on demand. Merging both offline into a single phase sequence enables stable manipulation along trajectories at a 1 ms update rate—to our knowledge, the first dynamic and purely field-based 6-DOF manipulation of non-spherical macroscopic bodies in the Mie and geometric regimes.

Our setup uses two opposing 16×16 PATs (Murata MA40S4S, $f = 40$ kHz, $\lambda \approx 8.7$ mm), vertically separated by $H = 197.40$ mm, giving $N = 512$ individually addressable transducers. Both PATs are based on the *Sonic Surface*³⁶ with two modifications. First, the original shift registers are replaced by Nexperia 74HC595D devices, whose higher specified shift-clock frequency enables the phase resolution to be increased from $\pi/16$ to $\pi/64$. Second, to overcome the 10.32 ms limit of the original serial interface,³⁷ the Cyclone IV E FPGA is replaced by a Skoll K7 module (Numato Lab) with an FTDI FT232RL chip (see Ref. 38), whose FT245 synchronous first in first out (FIFO) interface achieves burst-mode rates up to 18 MByte/s, matching Hirayama *et al.*³⁹ For deterministic 1 ms phase updates, the MATLAB interface was ported to C++ and Structured Text, executed on a programmable logic controller (PLC) (Beckhoff CX2042, TwinCAT 3.1). During operation, transducers and their drivers heat the arrays, which reduces the transducer resonance frequency and sensitivity and distorts the pressure field.⁴⁰ Cooling fans hold the PATs at a steady temperature, at which each array element was calibrated at 16 V_{pp} excitation voltage,⁴⁰ using a GRAS 46DP-11/8" pressure microphone on a 3-axis stage ($3 \times$ HPS 170, Physik Instrumente), a GRAS 12AK amplifier, and a Rohde & Schwarz HMO1024 oscilloscope. Two laser-cut wooden objects were used: a cross ($L_1 \times W_1 \times H_1 = 17.30 \times 2.15 \times 1.20$ mm = $2.0 \times 0.25 \times 0.14 \lambda$, $m_1 = 58$ mg) and a stick ($20.6 \times 2.0 \times 1.0$ mm = $2.37 \times 0.23 \times 0.115 \lambda$, $m_2 = 15$ mg). Both objects are symmetric. The force and torque model itself, however, assumes no symmetry and is formulated for triangulated surfaces of arbitrary shape. Triangular surface meshes

were generated with *Gmsh*⁴¹ for BEM computations. Object poses were tracked at 100 fps with a Sony Alpha 7 IV camera (FE 24–105 mm f/4.0 G) using a silhouette-based algorithm.

F_{rad} and T_{rad} are computed via Galerkin-BEM, extending the work of Inoue *et al.*¹² with an image-source model for inter-array reflections that is truncated after four reflections, so that $N_{\text{eff}} = 5N = 2560$ effective sources are considered for the calculation of the pressure field. As derived in the [supplementary material](#), F_{rad} and T_{rad} reduce to quadratic forms [see Eqs. (S34) and (S35)] in the transducer excitation vector $\mathbf{q} = (e^{i\phi_1}, \dots, e^{i\phi_N})^T \in \mathbb{C}^{N \times 1}$, whose matrix coefficients can be precomputed for a given object pose. In our experimental setup, the amplitude is fixed and only the transducer phases are used as the control variables. We therefore have to determine a phase vector $\boldsymbol{\phi} \in \mathbb{R}^{N \times 1}$ that produces a stable acoustic trap at position $\mathbf{r}_0$. This problem is conventionally posed as unconstrained nonlinear optimization.^{12–14} Unlike a sphere, whose geometry eliminates torques,¹² a non-spherical rigid body requires force and torque design for stable 6-DOF confinement. Force and torque equilibrium¹² at pose $\boldsymbol{\xi}_0 = (\mathbf{r}_0^T, \boldsymbol{\vartheta}_0^T)^T$ requires

$$\mathbf{F}_{\text{rad}}(\boldsymbol{\xi}_0) + \mathbf{F}_g = \mathbf{0}, \quad \mathbf{T}_{\text{rad}}(\boldsymbol{\xi}_0) = \mathbf{0}, \quad (1)$$

where $\boldsymbol{\vartheta} = (\vartheta_x, \vartheta_y, \vartheta_z)^T$ collects the principal-axis rotations and $\mathbf{F}_g \in \mathbb{R}^{3 \times 1}$ is the gravitational force. Linearization about $\boldsymbol{\xi}_0$ with $\mathbf{g} = (\mathbf{F}_{\text{rad}}^T, \mathbf{T}_{\text{rad}}^T)^T$ yields the local dynamics,

$$\mathbf{M} \ddot{\boldsymbol{\xi}} + \mathbf{B} \dot{\boldsymbol{\xi}} = \mathbf{J} \dot{\boldsymbol{\xi}}. \quad (2)$$

$\mathbf{M} = \mathbf{M}^T \succ \mathbf{0}$, $\mathbf{M} \in \mathbb{R}^{6 \times 6}$ is the mass-inertia matrix, $\mathbf{B} \in \mathbb{R}^{6 \times 6}$, $\mathbf{B} \succ \mathbf{0}$ the viscous damping, and $\mathbf{J} = (\partial \mathbf{g} / \partial \boldsymbol{\xi})|_{\boldsymbol{\xi}_0}$ the Jacobian, partitioned into 3×3 blocks $\mathbf{J}_{ij}$, $i, j \in \{1, 2\}$. For local asymptotic stability, it is sufficient that the symmetric part of the Jacobian is negative definite, $\frac{1}{2}(\mathbf{J} + \mathbf{J}^T) \prec \mathbf{0}$, and that its skew-symmetric part $\frac{1}{2}(\mathbf{J} - \mathbf{J}^T)$ vanishes. A Lyapunov-based analysis,³⁵ assuming viscous damping on all six degrees of freedom, establishes their sufficiency ([supplementary material](#)). We therefore determine $\boldsymbol{\phi}$ by minimizing a composite objective that targets force/torque equilibrium, a block-diagonal Jacobian with suppressed skew-symmetric coupling, and negative-definite stiffness across all degrees of freedom. Its full construction, including the pseudo-Huber and *squareplus* reformulation used for robust convergence, is given in the [supplementary material](#). As in related work, where L-BFGS proved effective,^{11–13,42} we minimize the reformulated objective function with respect to $\boldsymbol{\phi}$ via the L-BFGS-B-C solver⁴³ for its execution speed. [Figure 1](#) shows optimized pressure fields and experimental levitation for a wooden stick and cross. For each object, the optimization was performed on rotational keyframes sampled at 0.25° increments: about z over 180° (stick) or 90° (cross, by symmetry), and about x and y over $\pm 20^\circ$. The remaining DOFs are fixed at $\boldsymbol{\xi}_{\text{ref}} = (\mathbf{r}_{\text{ref}}^T, \boldsymbol{\vartheta}_{\text{ref}}^T)^T$ with $\mathbf{r}_{\text{ref}} = (0 \ 0 \ 100)^T$ mm and $\boldsymbol{\vartheta}_{\text{ref}} = (0^\circ \ 0^\circ \ 0^\circ)^T$. Phase vectors $\boldsymbol{\phi}$ are stored in a LUT for SDP retrieval.³² Beyond $\pm 20^\circ$, the optimized traps proved insufficiently robust, likely due to limited lateral forces and torques of the vertical PAT configuration. For LUT validation, the stick and cross were rotated about each principal axis in 1° increments (omitting x for the stick due to longitudinal symmetry). At each commanded pose, five frames were manually sampled from a single continuous levitation. The mean quantifies how closely the realized pose reproduces the commanded orientation, and the $\pm 1\sigma$ band characterizes the residual

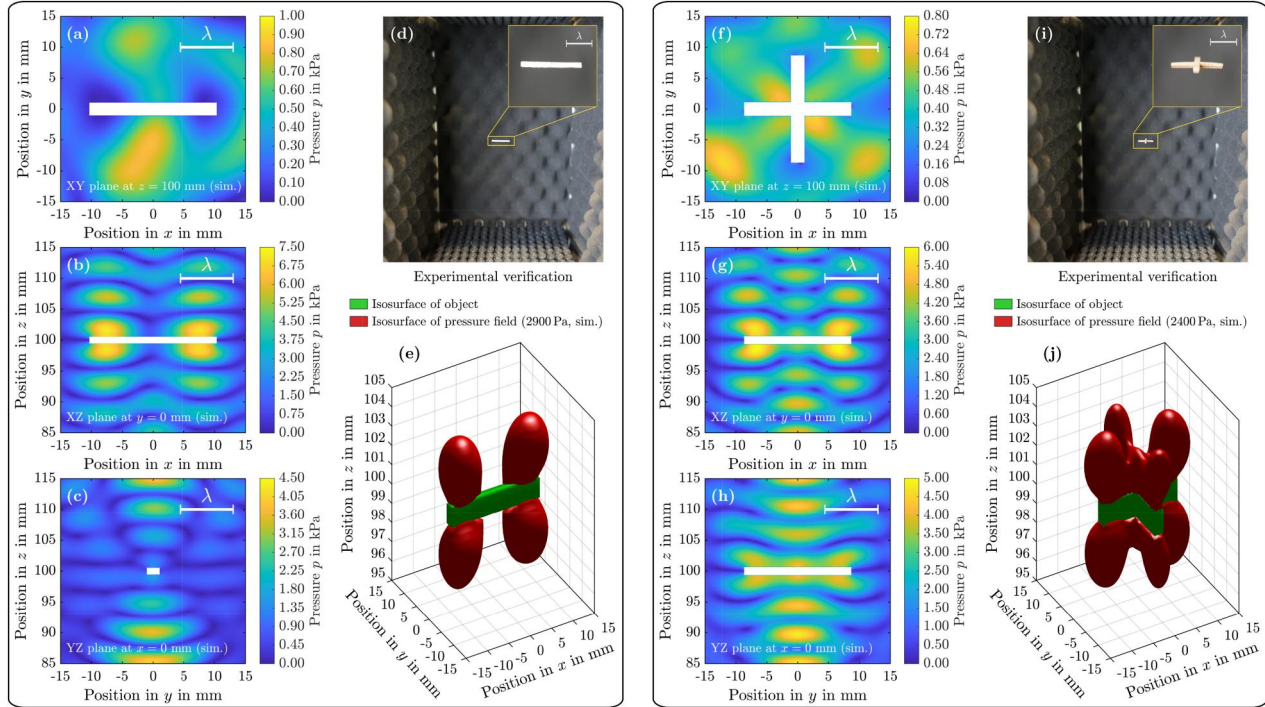


FIG. 1. Optimized pressure fields and experimental levitation of a wooden stick and cross. The simulated total pressure field of the optimized trap in the XY, XZ, and YZ planes at $16V_{pp}$ is shown for the stick in (a)–(c) and the cross in (f)–(h). Pressure-amplitude isosurfaces at 2900 and 2400 Pa (red), chosen to best visualize each trap geometry, appear in (e) and (j), together with the object surfaces (green). Photographs of the levitated objects at $r = (0\ 0\ 100)^T$ mm and $\vartheta = (0^\circ\ 0^\circ\ 0^\circ)^T$ are depicted in (d) and (i), respectively.

oscillation inside the trap. The levitation accuracy is quantified by a silhouette-based principal component analysis (PCA), with world-frame coordinates recovered via projective homography from a dot-grid (≥ 8 points, x/y axes) and a nine-point fit on the levitated cross (z axis, ≤ 0.11 mm RMS residual). For its in-plane orientation, where fourfold symmetry renders PCA ambiguous, the fourth angular harmonic with radial weighting was used instead. Figure 2 shows the angular error $\Delta\varphi_i = \varphi_{i,meas} - \varphi_{i,ref}$ vs reference $\varphi_{i,ref}$ for each rotation axis $i \in \{x, y, z\}$ and object. Sub-degree mean angular precision ($\bar{\sigma}_{\Delta\varphi} \leq 0.45^\circ$) is achieved across all axes and objects, with peak deviations $|\Delta\varphi|_{peak} \leq 2.82^\circ$ at the outer range, consistent with typical uncertainties of mid-air acoustic levitation (residual oscillations within the trap, transducer drift beyond calibration, and ambient variations). Overall, the LUT entries constitute reliable trap configurations.

We now examine the dynamic capabilities of the LUT–SDP architecture. To isolate its contribution, a kinematic feedforward control (no inertia, damping, or streaming considered) ensures that tracking errors reflect trap stiffness, not controller performance. From a single keyframe at ξ_{ref} , SDP translates the cross along two trajectories at rotational pose ϑ_{ref} : translation along the x axis [Figs. 3(a), 3(c), and 3(e); see video in the [supplementary material](#)] and an infinity symbol trajectory in the XZ plane [Figs. 3(b), 3(d), and 3(f); see video in the [supplementary material](#)]. The linear case, traversing ± 8 mm in 0.40 s per segment, demonstrates that the trap keeps the cross tightly confined during motion: $r_{x,ref}(t)$ is largely reproduced [Fig. 3(a)], and the deviation of $r_z(t)$ from $r_{z,ref} = 100$ mm stays within ± 0.25 mm

[Fig. 3(c)]. Numerical differentiation of $r_x(t)$ yields $v_x(t)$ [Fig. 3(e)], which captures magnitude and sign reversals of the reference motion. The infinity symbol trajectory is more demanding, as it varies continuously in speed and direction. Starting from $r_0 = (60\ 100)^T$ mm, the reference reads

$$\begin{aligned} r_{x,ref}(t) &= A \cos(\pi(1 - \cos(\omega t))), \\ r_{z,ref}(t) &= r_{z,0} + 0.5A \sin(2\pi(1 - \cos(\omega t))), \end{aligned} \quad (3)$$

where $A = 6$ mm, $\omega = \pi/8$ rad/s, and $t \in [0, 8]$ s. Without inertial compensation, the trajectory topology is preserved [Fig. 3(f)]; $r_x(t)$ and $r_z(t)$ track the reference with reduced accuracy [Figs. 3(b) and 3(d)], as expected for kinematic open-loop control. RMS tracking errors stay below $\sim 3\%$ of the cross length, comparable to typical self-oscillations of acoustically levitated objects.³⁷ The SDP-based translation stably manipulates the cross at $v_{x,max} \approx 40$ mm/s [Fig. 3(e)] within the working volume set by the force-to-weight margin, without object-specific dynamics. [Supplementary material](#) Video 3 shows continuous 6-DOF manipulation of the cross: ± 8 mm x/y -translations, a 7 mm circle in the XZ plane, and rotations about all three principal axes. SDP-translations of the non-rotated keyframe at r_{ref} and the BEM-precomputed rotational keyframes are merged offline and streamed to the phased array at 1 ms update rate without re-trapping. [Supplementary material](#) Video 4 demonstrates compositional LUT–SDP behavior with the stick by ± 8 mm translations along the x axis at non-trivial poses (45° about the z axis and 15° about the y axis).

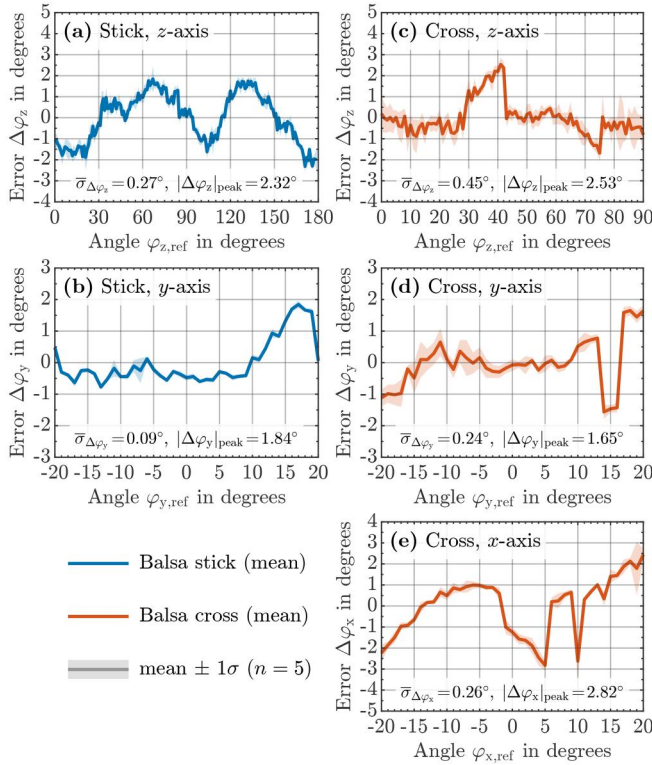


FIG. 2. Evaluation of rotational keyframes. (a)–(e) Angular error $\Delta\varphi_i = \varphi_{i,\text{meas}} - \varphi_{i,\text{ref}}$ for stick (blue) and cross (orange), $i \in \{x, y, z\}$. Curves: mean of $n = 5$ frames per pose, sampled from a single continuous levitation; bands: $\pm 1\sigma$. z axis rotations [(a) and (c)]: periodic residual from homography calibration (0.11 mm RMS). x and y axes [(b), (d), and (e)]: the precision $\sigma_{\Delta\varphi} \leq 0.26^\circ$ is far finer than the systematic offset $|\Delta\varphi|_{\text{peak}} \leq 2.82^\circ$, i.e., the equilibrium is well defined but shifted from the commanded angle. Stick yields a smaller σ than cross (stronger restoring forces/torques). Smooth within $|\varphi_{\text{ref}}| < 10^\circ$; beyond the image, jumps reflect weakened $F_{\text{rad}}/T_{\text{rad}}$ and local-minima variability.

Rotations and translations are commanded sequentially, with the stick returning to ϑ_{ref} between segments. The SDP framework thus operates at any LUT-sampled keyframe, not only at the non-rotated reference of Fig. 3 and [supplementary material](#) Video 3. Any reference trajectory can be reproduced within the reduced workspace if its rotational poses are in the LUT: SDP translates the incident pressure field of a stored phase pattern and inherits the trap topology but cannot synthesize new equilibria for unsampled poses. In practice, the available radiation force limits v_{max} of the reference trajectory. Concurrent translational and rotational motion, while feasible, reduces the stability margin of the trap and is avoided here.

In summary, we have demonstrated stable, dynamic 6-DOF manipulation of non-spherical macroscopic rigid bodies using a stationary phased array system, extending acoustic manipulation in the Mie and geometric regimes from sphere translation to full rotational control of non-spherical bodies. The architecture combines a Galerkin-BEM force/torque model (rotational keyframes via offline optimization) with SDP for translating the incident pressure field of the trap. The rotational keyframes and SDP-translated fields are merged offline into a phase sequence and streamed to the phased

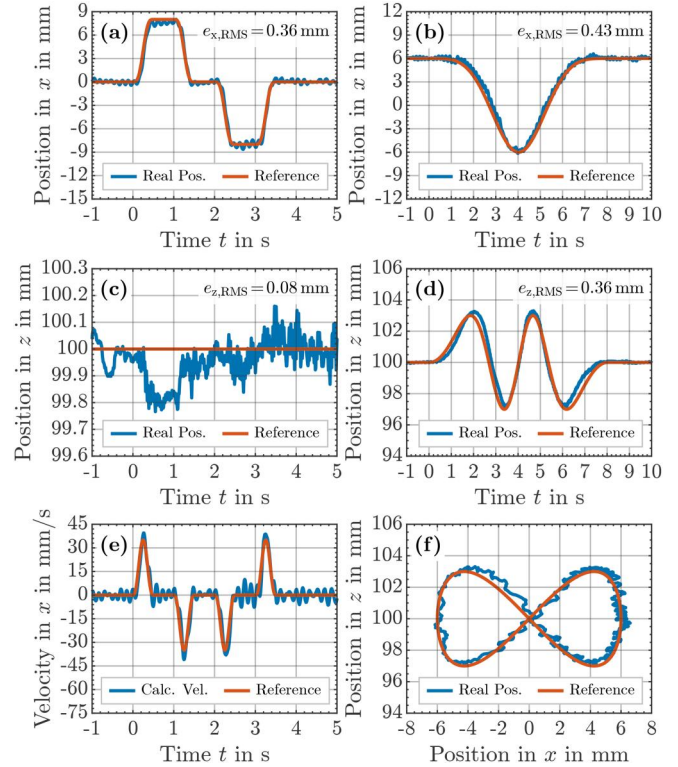


FIG. 3. Dynamic manipulation of the wooden cross. From a single keyframe at ξ_{ref}^* , the cross translates along two trajectories via SDP [greedy coordinate descent: $L = 1$, $i_{\text{max}} = (N + 1) \times 12$, $M = 154$] at 1 ms update rate. The linear trajectory [(a), (c), (e) and [supplementary material](#) Video 1] covers ± 8 mm along r_x in 0.40 s per segment with 0.50 s pauses, with panels showing $r_x(t)$, $r_z(t)$, and $v_x(t)$. For the infinity symbol trajectory [(b), (d), (f) and [supplementary material](#) Video 2], r_x and r_z start at r_0 and follow Eq. (3); the panels show $r_x(t)$, $r_z(t)$, and the XZ trace. RMS tracking errors $e_{x,\text{RMS}}$ and $e_{z,\text{RMS}}$ are annotated in (a) and (b) and (c) and (d), respectively.

array system at a 1 ms update rate. Experiments achieve sub-degree mean angular precision (Fig. 2) and translational tracking errors along $\sim 3\%$ of the object length (Fig. 3). [Supplementary material](#) videos 3 and 4 confirm stable manipulation of the wooden cross and stick across rotational and translational maneuvers without using an object-specific dynamic model. Future work focuses on accelerating and parallelizing the SDP algorithm. Its computational demand scales with the effective source count N_{eff} and surface mesh points M , both already much larger here ($N_{\text{eff}} = 2560$, $M = 154$) than in our original work ($N_{\text{eff}} = N = 256$, $M = 26$, single-sided, no image sources),³² making the $i_{\text{max}} \geq 2N$ iterations over the $N = 512$ transducer phases challenging online. Algorithmic and hardware acceleration would enable real-time execution at finer mesh resolutions and higher speeds, paving the way toward closed-loop control of levitated macroscopic objects in the Mie and geometric regimes.

See the [supplementary material](#) for the Galerkin-BEM computation of the acoustic radiation force and torque, the Lyapunov-based stability analysis of the acoustic trap, and the construction of the optimization objective. [Supplementary material](#) Videos 1 and 2 show the

linear and infinity symbol trajectories of the wooden cross, Video 3 shows a continuous 6-DOF maneuver in a single uninterrupted run, and Video 4 the composition of translations at non-trivial poses with the wooden stick.

The graphics in this manuscript were created using the package `export_fig`⁴⁴ with MATLAB R2023b. We thank Johannes Stadtherr (University of Augsburg) for fabricating the levitated objects and his valuable advice on the experimental setup. Moreover, the authors gratefully acknowledge financial support from the Bavarian State Ministry of Science and the Arts for funding of the AI Production Network Augsburg in the context of the High-Tech Agenda, the German Research Foundation (DFG) (Project No. 502189409), and the São Paulo Research Foundation (FAPESP) (Project No. 21/12848-0).

AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Sebastian Zehnter: Conceptualization (equal); Investigation (lead); Methodology (equal); Software (equal); Visualization (lead); Writing – original draft (lead); Writing – review & editing (equal). **Kevin Endres:** Conceptualization (equal); Methodology (equal); Software (equal); Writing – review & editing (equal). **Marco A. B. Andrade:** Funding acquisition (equal); Methodology (equal); Writing – review & editing (equal). **Christoph Ament:** Funding acquisition (equal); Supervision (lead); Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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