

Design and Development of a Spherical Motor for Conformal Printing of Curved Electronics

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Abstract—This paper presents the concept of a spherical-motor-based motion platform (SMP) for providing high-performance nozzle-substrate negotiation in conformal printing of curved electronics. Unlike conventional motion systems using serial/parallel mechanisms for multi-DOF rotations, a ball-joint-like spherical motor for providing continuous 3-DOF rotations in one joint is designed to meet the special needs of the conformal printing process. Both the kinematic and dynamic models of the SMP are presented for fitting into the conformal printing process. Specifically, the performance of a spherical motor has been evaluated, which shows better negotiation capability of the SMP than traditional motion systems. The experimental test results performed on a prototype spherical motor have validated the design concept.

Index Terms—Conformal printing, multi-DOF manipulation, spherical motor.

I. INTRODUCTION

THE conformal printing technology, which is capable of fabricating small-scale antennas [1], thin-film transistors [2], and interconnecting chips on flexible/curved substrates, provides a promising solution to meet the increasingly stringent design constraints for miniaturization and flexible trend of electric circuits in electronic industry. During the conformal printing process, features are formed by jet printing aerosol [3] or metallic ink [4], [5] onto the convex or concave surfaces [see Fig. 1(a)]. As the normal to the curvilinear surfaces constantly changes during printing, the position/orientation of the substrate must be precisely and smoothly manipulated in real time to align the surface normal to the nozzle while tracking the printing

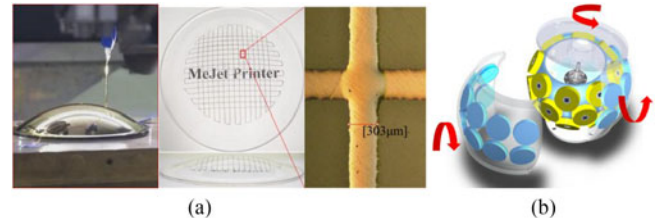


Fig. 1. Illustration of multi-DOF manipulation in conformal printing. (a) Printing of curved electronics. (b) Spherical motor.

trajectory to ensure uniform formation of the electric patterns, which presents unique fabrication challenges. Therefore, it is essential to develop a high-performance motion platform for high-quality conformal printing.

Existing motion systems for multi-DOF manipulation in manufacturing (mostly designed for metal-removal machining) are basically built by combining a multi-DOF rotational system and an XYZ stage. To achieve multi-DOF rotational motion, the most commonly adopted configurations consist of serially connected single-axis motors and mechanical linkages for coupling/transmission. These systems are usually bulky and costly and have singularities in their motion. An alternative is necessary for high-performance and efficient conformal printing process. First, unlike the machining usually dealing with surface processing where the effects of the singularities in motion systems can be avoided or reduced through tool path optimization or variable speed interpolation, the target features for conformal printing are mostly path-dependent [see Fig. 1(a)] and the jet printing process is very sensitive to the nozzle speed. Therefore, the nozzle paths are unique for most printing tasks and the printing must be regulated at constant speeds. A motion system with no singularity in its workspace is desired to ensure high printing quality. Second, the machining process is featured with large and abruptly changing forces on the cutter-workpiece interface. As a result, reduction gears and powerful motors are needed to increase the actuation stiffness to reject the disturbances. However, for the conformal printing featured with noncontact interface, the actuation power will mainly contribute to overcoming the structural inertia. Therefore, a system with simplified structure and small inertia is desired to improve system efficiency.

To overcome problems associated with conventional multi-DOF rotational systems, a variety of designs and systems have been proposed and developed. Among them are the ball-joint-

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like spherical motors [6]–[8] that are capable of providing continuous multi-DOF rotation in just one joint [Fig. 1(b)]. Originally proposed in [9] as a robotic wrist actuator, a variety of spherical motors have been developed and recent applications include actuator for digital cameras [10], a robotic joint [11], a reaction sphere actuator for satellite attitude control [12], a haptic interface for snap-fit designs [13] and a wheelchair traction motor [14]. By eliminating the transmission mechanisms, the spherical motors are featured with simple structures and reduced frictions/inertia, which is the key for dexterous motion with high dynamic performance. In order to achieve high-quality conformal printing, this paper explores the feasibility of using a spherical motor as a rotational system for developing a 6-DOF motion platform.

The remainder of this paper offers the following.

- 1) The design concept of a 6-DOF spherical-motor-based motion platform (SMP) for conformal printing is presented. To assist the design and analysis as well as a systematic evaluation, models and methods for applying the spherical motor to conformal printing are proposed.
 - a) A kinematic model characterizing the substrate-nozzle negotiation process is formulated for conformal printing and the inverse solutions for determining the joint motions for given printing trajectories are derived.
 - b) As a spherical motor is expected to translate in the SMP system, a dynamic model taking into account the motor center motion is established to extend the existing dynamic models of spherical motors [6]–[8], which are usually based on pure rotations with an assumption of stationary rotation centers.
 - c) A spherical motor is a multiport electromagnetic system transforming electrical inputs to multi-DOF rotational motions. A closed-form state-space representation characterizing the relationship among electrical variables (voltage/current) and motion variables in a spherical motor is derived, which not only provides a computationally efficient torque-to-current model for control, but also offers an effective means to evaluate the feasibility of printing parameters (trajectory and speed) for specified power limits of electrical hardware.
- 2) The performance of a prototype spherical motor for multi-DOF nozzle-substrate negotiation has been evaluated for a typical conformal printing configuration, which shows superior performance than conventional systems. The experimental tests have also validated the concept feasibility of the SMP for conformal printing.

II. DESIGN OF AN SMP FOR 6-DOF CONFORMAL PRINTING

Fig. 2(a) shows the conceptual design of an SMP for conformal printing. As shown in the figure, the ball-joint-like spherical motor [which is detailed in Fig. 2(b)] consists of a rotor and a stator. The socketlike rotor on which the substrate is mounted is supported concentrically on the stator and can rotate around the center C . The stator of the spherical motor is fixed to an X–Y

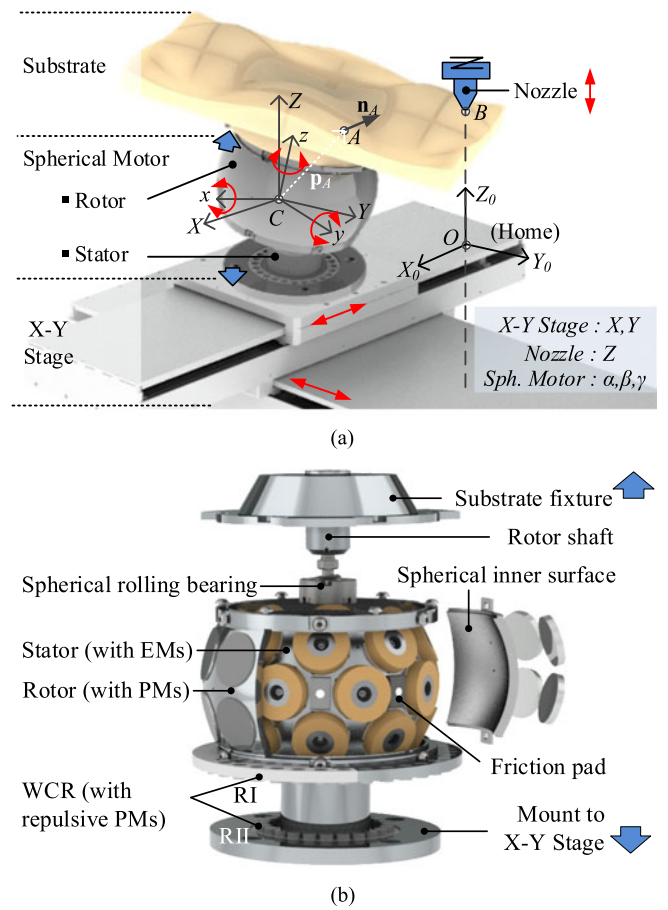


Fig. 2. SMP for conformal printing. (a) 6-DOF SPM. (b) CAD model of spherical motor (exploded view).

stage that translates horizontally. The nozzle, which moves in the vertical direction, can print electric patterns onto the curvilinear surface of the substrate manipulated by the SMP. The motion DOFs of the SMP are indicated in Fig. 2(a). While the X–Y stage and nozzle motions can be delivered with commercial linear modules, the key here is to develop a spherical motor to provide the desired rotational motions and to formulate the kinematic/dynamic models of the SMP for conformal printing. The spherical motor design, as well as the models and methods used in the design and analysis process, are addressed in the following sections.

A. 3-DOF Spherical Motor Design

Fig. 2(b) shows the computer-aided-design (CAD) model of the spherical motor. The rotor consisting of four dome-shaped plates is supported on the stator with a low-friction spherical rolling bearing allowing for continuous 3-DOF rotational motion. The rotor orientation is defined in terms of roll, pitch, and yaw Euler angles $\mathbf{q} = [\alpha, \beta, \gamma]^T$. The ball-like stator consists of three layers of air-cored cylindrical electromagnets (EMs); and the rotor consists of two layers of cylindrical permanent magnets (PMs) embedded in the recessed holes of the rotor plates. All the axes of the EMs and PMs radially pass through the motor center. In spherical coordinates, the centroids of the EMs and

PMs are defined in stator XYZ and rotor xyz frames, respectively, using (1), where R , Θ , and Φ are the radial distance, azimuth angle, and polar angle, respectively

$$\vec{C} = [R \sin \Theta \cos \Phi, R \sin \Theta \sin \Phi, R \cos \Theta]^T. \quad (1)$$

As the rotor (when mounted with the substrate) is essentially an inverted pendulum (at no current inputs), a weight compensating regulator [WCR as indicated in Fig. 2(b)] is incorporated to support the rotor/substrate against gravity by means of magnetic repulsion. As shown in the figure, the WCR consists of two circular rings (RI and RII) embedded with cylindrical PMs circumferentially spaced on the rotor and stator, respectively. The PMs in RI and RII are designed to have like polarities facing each other, which acts like a nonlinear spring to angularly support the rotor and tend to maintain the rotor at its equilibrium (zero inclination).

In order to allow the rotor/substrate to maintain at any orientation (usually at the beginning or end of a printing task) without constantly energizing the spherical motor, a locking mechanism with friction pads are designed that can be pushed out radially in the midplane of the stator to press against the rotor inner surface. The rotor plates are designed to have spherical inner surfaces to assure good contact of the friction pads.

B. 6-DOF Substrate-Nozzle Negotiation Kinematics

In order to achieve high-level line/surface topology and electric feature with good quality, the substrate must be precisely and continuously manipulated in multi-DOF so that the nozzle tip follows the printing trajectory and the surface normal to the printing point always aligns with the nozzle axis during the whole process. To begin the formulation of the kinematic model for describing the substrate-nozzle negotiation, the coordinate systems are defined in Fig. 2(a). As shown in the figure, $X_0Y_0Z_0$ is the home coordinate frame where the nozzle moves along Z_0 -axis; XYZ and xyz represent the stator and the rotor coordinate frames of the spherical motor with the origins assigned at the motor center C . At initial state, XYZ and xyz coincide with $X_0Y_0Z_0$. During the printing process, for a point-to-print A on the substrate with its local position and surface normal denoted with $\mathbf{p}_A = [x_A, y_A, z_A]^T$ and $\mathbf{n}_A = [n_{Ax}, n_{Ay}, n_{Az}]^T$ with respect to the rotor frame xyz [see Fig. 2(a)], the position and the direction of the surface normal to A can be expressed in (2a) and (2b) with respect to the following home coordinate:

$$\mathbf{P}_A = [\mathbf{R}(\alpha, \beta, \gamma)]^T \mathbf{p}_A + \mathbf{P}_C \quad (2a)$$

$$\mathbf{N}_A = [\mathbf{R}(\alpha, \beta, \gamma)]^T \mathbf{n}_A \quad (2b)$$

where

$$[\mathbf{R}(\alpha, \beta, \gamma)] = \begin{bmatrix} C_\gamma C_\beta & S_\gamma C_\alpha + C_\gamma S_\beta S_\alpha & S_\gamma S_\alpha - C_\gamma S_\beta C_\alpha \\ -S_\gamma C_\beta & C_\gamma C_\alpha - S_\gamma S_\beta S_\alpha & C_\gamma S_\alpha + S_\gamma S_\beta C_\alpha \\ S_\beta & -C_\beta S_\alpha & C_\beta C_\alpha \end{bmatrix}. \quad (2c)$$

In (2a) and (2b), S and C denote sine and cosine, respectively; and the vector $\mathbf{P}_C = [X_C, Y_C, Z_{C0}]^T$ represents the position

of the rotation center of the spherical motor where the horizontal displacements (X_C, Y_C) are determined by the X - Y stage; and Z_{C0} is constant. $\mathbf{R}$ is the rotation matrix expressed in terms of the rotor Euler angles (α, β, γ). The negotiation for positioning and aligning can be mathematically expressed as follows:

$$\mathbf{P}_A = \mathbf{P}_B = [0 \quad 0 \quad Z_B]^T \quad (3a)$$

$$\mathbf{N}_A = [0 \quad 0 \quad 1]^T. \quad (3b)$$

In (3a), Z_B represents the vertical displacement of the nozzle while the nozzle axis stays upright constantly. Substituting (2a) and (2b) into (3a) and (3b) leads to three independent equations (4a)–(4c) governing the translation and two independent equations (4d) and (4e) governing the rotation

$$\text{Translation: } C_\gamma C_\beta x_A - S_\gamma C_\beta y_A + S_\beta z_A + X_C = 0 \quad (4a)$$

$$(S_\gamma C_\alpha + C_\gamma S_\beta S_\alpha) x_A + (C_\gamma C_\alpha - S_\gamma S_\beta S_\alpha) y_A - C_\beta S_\alpha z_A + Y_C = 0 \quad (4b)$$

$$(S_\gamma S_\alpha - C_\gamma S_\beta C_\alpha) x_A + (C_\gamma S_\alpha + S_\gamma S_\beta C_\alpha) y_A + C_\beta C_\alpha z_A + Z_{C0} = Z_B \quad (4c)$$

$$\text{Rotation: } C_\gamma C_\beta n_{Ax} - S_\gamma C_\beta n_{Ay} + S_\beta n_{Az} = 0 \quad (4d)$$

$$(S_\gamma S_\alpha - C_\gamma S_\beta C_\alpha) n_{Ax} + (C_\gamma S_\alpha + S_\gamma S_\beta C_\alpha) n_{Ay} + C_\beta C_\alpha n_{Az} = 1. \quad (4e)$$

Equations (4a)–(4e), referred to here as the kinematic model of the conformal printing process, characterize the relationship between the printing feature ($\mathbf{p}_A$ and $\mathbf{n}_A$, which are in the substrate space) and the rotational/translational (R/T) displacements ($X_C, Y_C, Z_B, \alpha, \beta, \gamma$, which are defined in the SMP motion space). To complete a printing task, an inverse solution to determine the R/T displacements for specified ($\mathbf{p}_A, \mathbf{n}_A$) is required. For the kinematic model (4a)–(4e), as there are more variables (six-dimensional (6-D) R/T displacements) than the number of equations, an optimal solution can be determined by minimizing the total R/T displacements. Two inverse solutions in different optimization dimensions are proposed as follows.

1) INV1: Full Dimension Optimization (Simultaneous 6-DOF): For the k th point on the printing trajectory, the R/T displacements can be solved simultaneously with (4a)–(4e) while minimizing a cost function in the form of (5) representing the sum of the squared incremental travel distances in all six DOFs

$$f = w_1(\alpha_k - \alpha_{k-})^2 + w_2(\beta_k - \beta_{k-})^2 + w_3(\gamma_k - \gamma_{k-})^2 + w_4(X_{Ck} - X_{Ck-})^2 + w_5(Y_{Ck} - Y_{Ck-})^2 + w_6(Z_{Bk} - Z_{Bk-})^2. \quad (5)$$

In (5), the subscripts of the motion variables “ k ” and “ $k-$ ” represent the k th and its previous states, respectively; and w_1 – w_6 are weighting coefficients (constants) on the R/T displacements.

2) INV2: Reduced Dimension Optimization: In (4a)–(4c), the translational motion is fully defined (three variables and three equations) when the rotational displacements are known. Therefore, the inverse can be found with the following two steps:

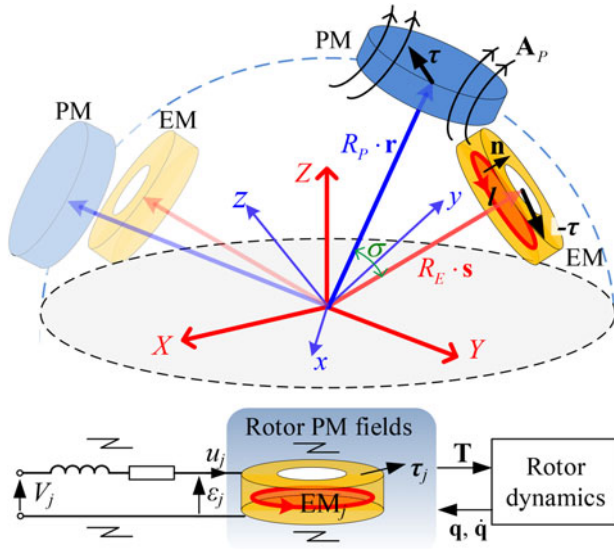


Fig. 3. Pole configuration and multiport formulation.

- 1) optimize (α, β, γ) by minimizing the cost function (5) with w_4, w_5 , and $w_6 = 0$ subject to the constraints (4d)–(4e); and
- 2) solve (X_C, Y_C, Z_B) from (4a)–(4c) with the (α, β, γ) values obtained in step 1).

C. Rotor Dynamics of the Spherical Motor

The dynamic model of the spherical motor taking into account the effects of the motor translations can be derived with Lagrange formulation, which has the following form:

$$\mathbf{M}\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q}, \dot{\mathbf{q}}) + \mathbf{g}(\mathbf{q}) = \mathbf{T} - \mathbf{D}(\mathbf{q}, \ddot{\mathbf{x}}) - \mathbf{T}_r. \quad (6)$$

In (6), $\mathbf{q} = (\alpha, \beta, \gamma)^T$ and $\mathbf{x} = [X_C, Y_C, Z_{C0}]^T$ are the R/T displacements of the rotor; $\mathbf{M}$ is the rotor inertia matrix; $\mathbf{C}(\mathbf{q}, \dot{\mathbf{q}})$ is the combined centripetal and Coriolis torque vector; $\mathbf{g}(\mathbf{q})$ is the gravitational torque vector; $\mathbf{D}(\mathbf{q}, \ddot{\mathbf{x}})$ is the torque vector representing the effect of the motor displacement; $\mathbf{T}_r$ is the restoring torque of the repulsive WCR rings; and $\mathbf{T}$ is the electromagnetic actuating torque applied on the rotor. The derivation of the dynamic model as well as the explicit expressions of the terms in (6) is detailed in the appendix.

D. Multiport Formulation for Spherical Motor

Fig. 3 shows the typical pole configuration of a spherical motor and the multiport diagram illustrating the operational principle of the system. The stator-EMs are surrounded by the magnetic fields of the rotor PMs. When the EMs are applied with electrical power (denoted by voltage V and current u), Lorentz forces will be generated by the current-carrying EMs that translate into a torque on the rotor. The torque leads to rotor motions that are governed by the rotor dynamic model (6).

In Fig. 3, XYZ and xyz represent the stator and rotor frames of the spherical motor; $\mathbf{s}$ and $\mathbf{r}$ represent the unit vectors in XYZ frame from the origin to the geometrical centers of the EMs and PMs, respectively; and σ is the separation angle between $\mathbf{s}$ and $\mathbf{r}$.

For an EM–PM pair, as shown in Fig. 3, the total magnetic flux linkage (MFL) through the EM can be obtained as follows [15]:

$$\Lambda = \frac{1}{a} \int_V (\mathbf{A}_P \cdot \mathbf{l}) dv. \quad (7)$$

In (7), $\mathbf{A}_P$ is the magnetic vector potential of the PM (see the appendix); the EM consists of contiguous wire conductors where $\mathbf{l}$ is the directional vector of the current and a and V denote the wire cross-sectional area and winding volume, respectively. As the PM and EM are axis symmetric, the MFL contributed by the PM only depends on the EM–PM separation angle σ . The relationship can be characterized by a kernel function f derived by normalizing (7) with respect to the PM magnetization λ

$$f(\sigma) = \frac{\Lambda}{\lambda} = \frac{1}{a\lambda} \int_V (\mathbf{A}_P \cdot \mathbf{l}) dv \quad (8)$$

where

$$\sigma = \cos^{-1}(\mathbf{r} \cdot \mathbf{s}) \quad (9a)$$

and

$$\mathbf{r} = [\mathbf{R}]^T \mathbf{p}. \quad (9b)$$

In (9b), $\mathbf{p}$ is a constant vector representing coordinates of the PM vector $\mathbf{r}$ with respect to the local rotor frame xyz ; $[\mathbf{R}]$ is the rotation matrix of the rotor with the same definition as in (2c). Without loss of generality, the total MFL in the j th EM contributed by all N_P PMs in the spherical motor can be characterized by (10a), based on which the magnetic energy stored in EM_j can be derived as (10b) [16]

$$\Lambda_j = \sum_{l=1}^{N_P} \lambda_l f(\sigma_{j,l}) \quad (10a)$$

$$W_j = u_j \Lambda_j. \quad (10b)$$

In (10a) and (10b), $\sigma_{j,l}$ refers to the separation angle between the j th EM (EM_j) and l th PM (PM_l); and u_j is current input of EM_j . According to (9a) and (9b), $\sigma_{j,l}$ is $\mathbf{q}$ -dependent and therefore Λ_j in (10a) and (10b) is also a function of $\mathbf{q}$.

Based on Faraday's law of induction and the principle of virtual displacement [17], the electromotive force ε induced in EM_j and the magnetic torque applied on the rotor by EM_j can be derived as (11a) and (11b) by taking the derivative of (10a) and (10b) with respect to time and $\mathbf{q}$, respectively

$$\varepsilon_j = -d\Lambda_j/dt = -\Lambda'_j(\mathbf{q}) \dot{\mathbf{q}} \quad (11a)$$

$$\tau_j = dW_j/d\mathbf{q} = u_j \Lambda'_j(\mathbf{q}). \quad (11b)$$

In (11a) and (11b), $\Lambda'_j(\mathbf{q}) = d\Lambda_j/d\mathbf{q}$, which can be expressed explicitly as (12a) based on (9a) and (10a)

$$\Lambda'_j(\mathbf{q}) = \sum_{l=1}^{N_P} \left(\Theta_{lj} \begin{bmatrix} s_j^T \mathbf{a}_l \\ s_j^T \mathbf{b}_l \\ s_j^T \mathbf{c}_l \end{bmatrix} \right) \quad (12a)$$

where

$$\Theta_{lj} = \frac{\lambda_l f'(\sigma_{lj})}{\sqrt{1 - (\mathbf{r}_l \cdot \mathbf{s}_j)^2}}. \quad (12b)$$

In (12a) and (12b); $\mathbf{a} = \partial \mathbf{R} / \partial \alpha$, $\mathbf{b} = \partial \mathbf{R} / \partial \beta$, $\mathbf{c} = \partial \mathbf{R} / \partial \gamma$, and $f' = df/d\sigma$.

Based on (11a), the total voltage across EM_j can be expressed as (13); and for a magnetically linear system (with no saturation), the total torque applied on the rotor is the sum of the electromagnetic torques (11b) contributed by each EM, which can be expressed as (14)

$$V_j = R_j u_j + L_j \dot{u}_j + \Lambda'_j(\mathbf{q}) \cdot \dot{\mathbf{q}} \quad (13)$$

$$\mathbf{T} = \sum_{j=1}^{N_E} \tau_j = \mathbf{A} \mathbf{u} \quad (14)$$

where

$$\mathbf{A} = [\Lambda'_1(\mathbf{q}), \dots, \Lambda'_j(\mathbf{q}), \dots, \Lambda'_{N_E}(\mathbf{q})] \quad (14a)$$

and

$$\mathbf{u} = [u_1, \dots, u_j, \dots, u_{N_E}]^T. \quad (14b)$$

In (13), R_j and L_j are resistance and the self-inductance of EM_j , respectively, and the mutual inductances of the EMs in the spherical motor are neglected. With $\Lambda'_j(\mathbf{q})$ expressed explicitly using (12a) and (12b), (13) and (14) present a closed-form formulation and state-space representation to characterize the dynamic relationship among the electrical variables (V_j , u_j) and motion variables ($\mathbf{T}$, $\mathbf{q}$, $\dot{\mathbf{q}}$) in a spherical motor, which provides an in-depth means for comprehensively evaluating the spherical motor performance for conformal printing.

Based on the current-to-torque relationship in (14), for a spherical motor featured with redundant inputs (the number of current inputs is higher than its DOFs), an optimal $\mathbf{u}$ minimizing the total input energy for any specified torque $\mathbf{T}$ can be determined from (15) in the form of pseudoinverse

$$\mathbf{u} = [\mathbf{A}]^T \left([\mathbf{A}] [\mathbf{A}]^T \right)^{-1} \mathbf{T}. \quad (15)$$

Equations (14) and (15) referred here are as the forward and inverse torque models of the spherical motor.

III. RESULTS AND DISCUSSION

A prototype spherical motor (shown in Fig. 4) has been developed based on the CAD model presented in Fig. 2(b). With the design specifications summarized in Table I, the performance of the spherical motor and the feasibility of the SMP for conformal printing were investigated with both numerical simulations and experimental verifications.

A. System Parameters

Fig. 5(a) shows a schematic illustrating the design parameters of the rotor/substrate centroid as well as the WCR dimensions. The parameter values and those defining the EM-PM locations

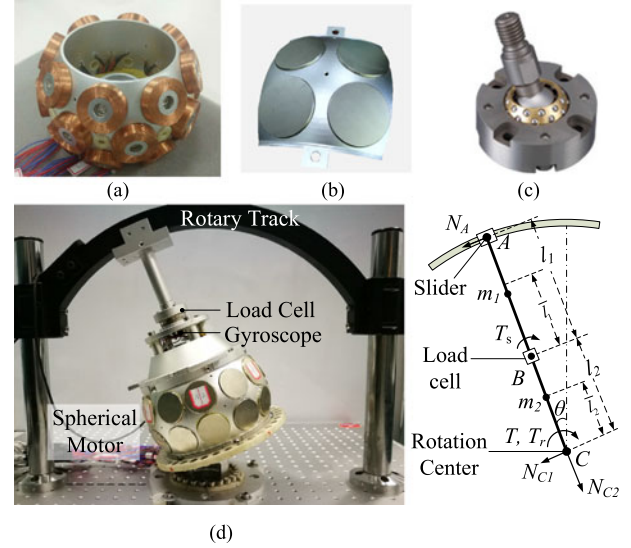


Fig. 4. Spherical motor prototype and torque model test setup. (a) Stator (b) Rotor plate (1/6). (c) Spherical joint. (d) Torque test setup and schematic.

TABLE I
DESIGN SPECIFICATIONS

Overall printing objectives	Line errors Line speed Printing range	20 μm 100 mm/s 300 mm $\times$ 400 mm
Linear module spec.	Maximum speed Positioning error	0.5 m/s 5 μm
Current amp. spec.	Max. current (each channel) Max. voltage (each channel) Maximum power (total)	8 A 24 V 2000 W

in (1) are listed in Table II. To facilitate the numerical investigation and implementation, the model parameters are presented in the following.

1) Substrate: A substrate [see Fig. 2(a)] with a typical curvilinear surface was selected for illustrating the conformal printing process. The numerical model of the substrate surface was obtained with the features ($\mathbf{p}$, $\mathbf{n}$) for each point on the surface defined in the rotor frame xyz . The top surface of the substrate is depicted in Fig. 5(b) for visualization.

2) Kernel Function: The computation of the multiport model (12)–(15) requires an explicit form of the kernel function f . Following (8), the MFL of an EM-PM pair in the spherical motor [as shown in Fig. 3(a)] was computed with numerical integration using the EM-PM parameters presented in Fig. 5(a) and Table II. A closed-form expression can be obtained as (16) by curve fitting the numerical results

$$f(\sigma) = \sum_{j=0}^7 [a_j \cos(jw\sigma) + b_j \sin(jw\sigma)]. \quad (16)$$

In (16), $[a_0 - a_7] = [3.4, 2.2, -2.6, -0.5, 1.3, 0.3, -0.1, -0.02] \times 10^{-2}$, $[b_1 - b_7] = [-4.5, -0.7, 2.3, 0.5, -0.5, -0.1, 0.02] \times 10^{-2}$, and $w = 0.07$. The numerically computed results with (8) are compared with the curve-fitted results in Fig. 5(c). f' in (12b) can be derived explicitly by taking the derivative of (16).

TABLE II
SPHERICAL MOTOR PARAMETERS

$a_o = 40, l = 6, \mu_0 M_0 = 1.465 \text{ T}$				
Rotor PMs (NdFeB)	PM ₁ centroid $R_P = 87.4$	Index (l) 1–12 13–24	(Θ, Φ) in xyz 105° 75°	Polarity, $\lambda/(\mu_0 M_0)$ $(-1)^j$ $(-1)^{j-1}$
$a_o = 40, a_i = 14, l = 10, a = 0.5, \# \text{ of turns}: 520$				
Stator EMs	EM _j centroid $R_E = 75.4$	Index (j) 1–8 (bottom) 9–16 (top) 17–24 (middle)	(Θ, Φ) in XYZ 116° 64° 90°	$(j-1) \times 45^\circ$ $(j-9) \times 45^\circ$ $(j-17) \times 45^\circ + 22.5^\circ$
WCR	RI (with rotor): $a_o = 10, l = 10, \mu_0 M_0 = 1.465 \text{ T}$ $h_1 = 50.05, r_1 = 91, \# \text{ of PMs (equally spaced): } 36$ RII (with stator): $a_o = 10, l = 15, \mu_0 M_0 = 1.22 \text{ T}$ $h_2 = 117.9, r_2 = 46, \# \text{ of PMs (equally spaced): } 24$			
Rotor/ substrate	Mass: $m = 7.41 \text{ kg}$ (rotor 3.06 kg, substrate 4.35 kg) Centroid: $h_z = 62.1$ Moment of inertia ($\text{kg}\cdot\text{m}^2$): $I_{xx} = 0.055, I_{yy} = 0.09, I_{zz} = 0.105$			

Units in mm otherwise denoted.

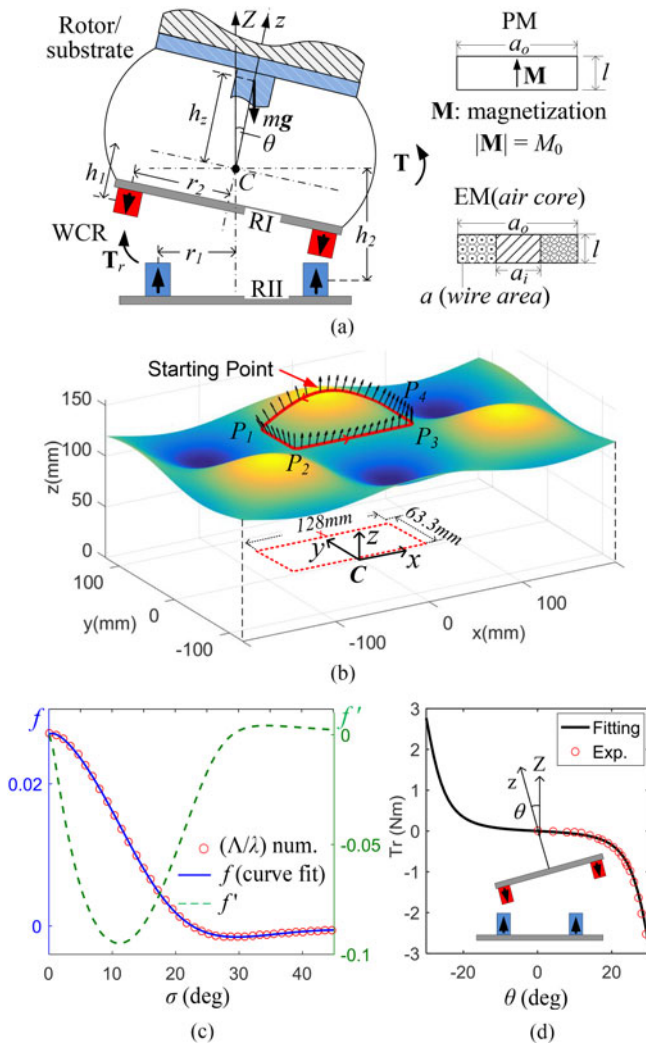


Fig. 5. Illustration of system parameters. (a) Schematic of model parameters. (b) 3-D substrate surface and illustrative printing trajectory. (c) Kernel function. (d) Restoring torque of WCR.

3) Restoring Torque of WCR: As the repulsive rings of the WCR generate circumferentially uniform magnetic fields, the restoring torque T_r of the WCR is equivalent to an inclinational torque normal to the inclination plane [formed by z and Z axes in Fig. 5(a)], which has the following form:

$$T_r = T_r(\theta) \begin{bmatrix} C_\beta S_\alpha / \sqrt{S_\alpha^2 + S_\beta^2 C_\alpha^2} & S_\beta C_\alpha / \sqrt{S_\alpha^2 + S_\beta^2 C_\alpha^2} & 0 \end{bmatrix}^T \quad (17a)$$

where

$$\theta = \cos^{-1}(C_\beta C_\alpha). \quad (17b)$$

In (17a) and (17b), θ is the inclinational angle, and $T_r(\theta)$ is a function characterizing the relationship between the inclinational torque and θ . An explicit form of $T_r(\theta)$ was found by curve fitting the measured torques, as illustrated in Fig. 5(d).

B. Investigation of the Inverse Kinematic Model

The forward/inverse kinematic models were validated that allows for a justified evaluation of the SMP performance.

For illustration, a printing trajectory, as shown in Fig. 5(b), was used to simulate the substrate-nozzle negotiation process. With the printing features (p_A , n_A) extracted from the specified trajectory, the R/T displacements of the SMP were numerically computed with the proposed inverse kinematic models (*INV1* and *INV2* in Section II-B) for printing each point on the trajectory. In order to unify the rotational and translational motions, the weights of the rotational displacements in the cost functions (5) are multiplied with the rotor radius R_0 . In particular, to compare the SMP with conventional five-axis motion platform (which is equivalent to the case when β is fixed), the R/T displacements for five-axis configuration were simulated by simultaneously solving five variables (X_C , Y_C , Z_B , α , γ) with (4a)–(4e) for $\beta = 0$. In Fig. 6(a), the computed results are plotted as a function of the path length s . It can be seen that the R/T displacements (computed using both *INV1* and *INV2*)

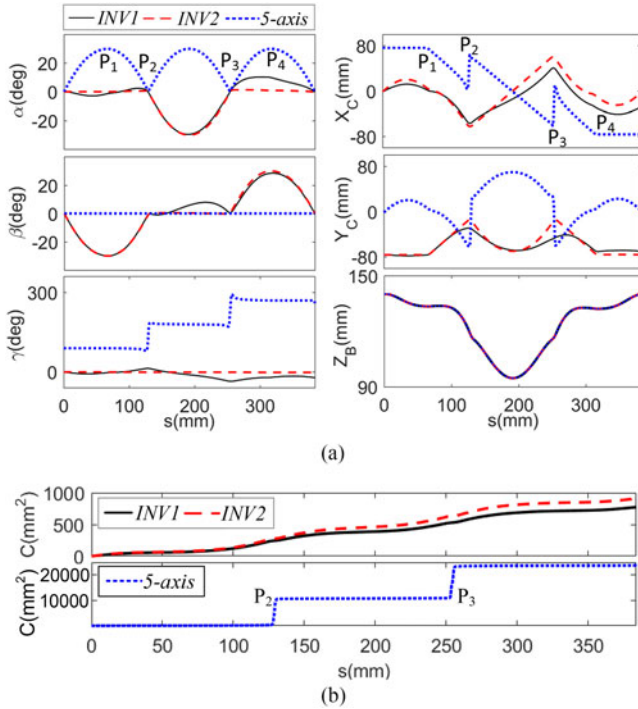


Fig. 6. Illustration of inverse kinematics. (a) SMP motions (s is the path length). (b) Comparison of sum of R/T displacements on all axes.

TABLE III
SIMULATION PARAMETERS ($R_0 = 91$ mm)

	Weights of cost function	Avg. Comp. time
INV1	$w_1 = w_2 = w_3 = R_0^2, w_4 = w_5 = w_6 = 1$	102.3 ms
INV2	$w_1 = w_2 = w_3 = R_0^2$	66.7 ms

are continuous while singularities can be observed for five-axis configuration [P_2, P_3 in Fig. 6(a), corresponding to the corners indicated in Fig. 5(b)]. Meanwhile, the SMP is much more efficient as demonstrated by the much smaller motion costs in Fig. 6(b) where the sum of the total R/T displacements (on all axes) were compared. In terms of the SMP motion planning, INV1, which is based on 6-D optimization, shows slightly less R/T displacements than INV2, but at the cost of around 53% more computational time (as summarized in Table III). Therefore, INV2 is selected as the inverse solution for the subsequent discussions.

C. Actuation Performance Investigations

The capability of the spherical motor for driving the rotor/substrate to complete a printing task was tested by simulating and analyzing the key parameters with the multi-port model (13)–(15).

1) Static Loading Test: The capability of the spherical motor for statically supporting the rotor/substrate in the entire workspace was simulated. At equilibrium, the dynamic model (6) reduces to the following:

$$\mathbf{T} - \mathbf{T}_r = \mathbf{g}(\mathbf{q}). \quad (18)$$

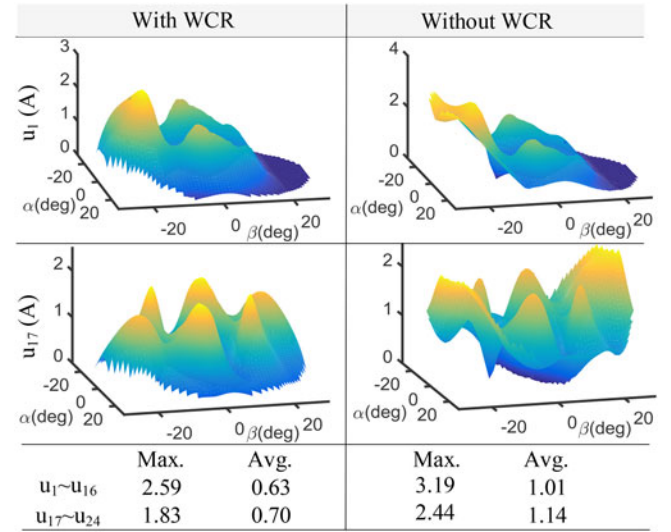


Fig. 7. Simulated currents (in amperes) for static loading.

With $\mathbf{T}_r$ defined in (17a) and $\mathbf{g}(\mathbf{q})$ in (6) defined in the appendix, the desired actuation torque for statically supporting the rotor/substrate was calculated in the entire working space

$$-30^\circ \leq \alpha, \beta \leq 30^\circ, 0 \leq \gamma \leq 360^\circ.$$

The currents for generating the desired torque were derived with (15) where the $\mathbf{A}$ components were computed using (12a) and (14a) with the kernel function given in (16).

The simulation results are presented in Fig. 7 where the current profiles of two EMs (EM1 and EM17 located on bottom and middle layers of the stator, respectively) were depicted for demonstration. The left and right columns of Fig. 7 compare the cases for the spherical motor design with and without WCR. To assist visualization, each point represents the maximum current for the orientations in the range ($\alpha, \beta, 0 \leq \gamma \leq 360^\circ$), and the maximum and average currents in the entire range are summarized for all EMs in Fig. 7. Due to symmetry, the current profiles are periodic for the EMs in the top/bottom layers ($u_1 - u_{16}$) and the midlayer ($u_{17} - u_{24}$), respectively, and the maximum and average values are the same. It can be seen that the WCR can effectively decrease the currents especially at large inclinations. The rotor/substrate can be statically supported in the entire workspace with a maximum current at 2.59 A for the design.

2) Dynamic Response: The dynamic responses for printing the specified trajectory in Fig. 5(b) were simulated, which provides a quantitative evaluation of the feasibility of the specified printing configuration (trajectory and speed) to prevent voltage saturations (which may lead to current/torque distortions). Assuming a printing speed at 100 mm/s, the time responses of the motion states of the spherical motor for performing the specified printing trajectory in Fig. 5(b) were obtained by interpolating in the s -dependent Euler angles in Fig. 6(a). With the obtained motion states (illustrates in Fig. 8), the desired torque $\mathbf{T}$ was computed with the dynamic model (6) and the current inputs and the EM voltages were computed with (15) and (13),

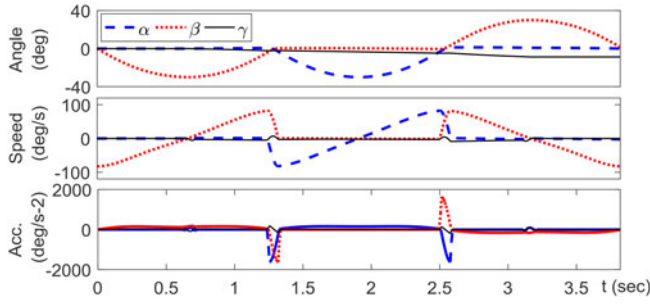


Fig. 8. Illustration of motion states (interpolation of INV2 in Fig. 6(a) for printing speed at 100 mm/s).

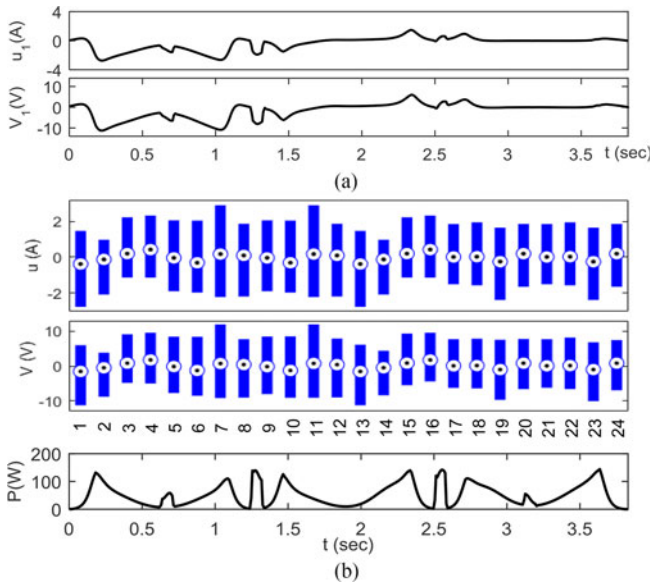


Fig. 9. Dynamic responses. (a) Current and voltage of EM₁ (in bottom layer of stator). (b) Current and voltage statistics and total power of all EMs.

respectively. As an illustration, the current and voltage of EM₁ were plotted as a function of time in Fig. 9(a). The statistics of currents and voltages of all 24 EMs are summarized in Fig. 9(b) where the circles denote the averages over time. The total electrical input power of the spherical motor (sum of the products of voltage by current of each EM) is also plotted in Fig. 9(b). The simulation results show that the specified printing trajectory can be completed at current and voltage within 3 A and 12 V and the maximum total input power less than 150 W. Comparing the simulated results to the current amplifier specifications listed in Table I implies that the specified printing parameters are feasible.

D. Sliding-Mode Control for Orientation Tracking

To achieve high-quality printing, the spherical motor must be able to precisely follow the desired Euler angles commanded by the inverse kinematic model. As the rotor dynamics (6) of the spherical motor is highly nonlinear, a sliding mode controller is selected for its capability of dealing with the nonlinearities as well as its robustness for system uncertainties.

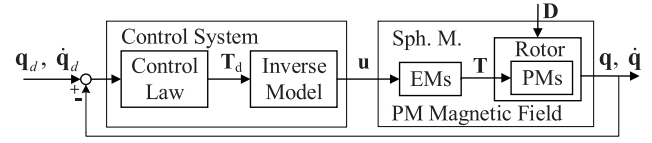


Fig. 10. Control diagram.

The dynamic model (6) can be rewritten as (19) considering the model uncertainties as illustrated in (19b)–(19f)

$$\mathbf{M}_0 \ddot{\mathbf{q}} + \mathbf{C}_0(\mathbf{q}, \dot{\mathbf{q}}) + \mathbf{g}_0(\mathbf{q}) = \mathbf{T} + \boldsymbol{\rho} - \mathbf{D}_0 - \mathbf{T}_{r0} \quad (19)$$

where

$$\boldsymbol{\rho} = -\Delta \mathbf{M} \ddot{\mathbf{q}} - \Delta \mathbf{C}(\mathbf{q}, \dot{\mathbf{q}}) - \Delta \mathbf{g}(\mathbf{q}) - \Delta \mathbf{D} - \Delta \mathbf{T}_r \quad (19a)$$

$$\mathbf{M} = \mathbf{M}_0 + \Delta \mathbf{M} \quad (19b)$$

$$\mathbf{C}(\mathbf{q}, \dot{\mathbf{q}}) = \mathbf{C}_0(\mathbf{q}, \dot{\mathbf{q}}) + \Delta \mathbf{C}(\mathbf{q}, \dot{\mathbf{q}}) \quad (19c)$$

$$\mathbf{g}(\mathbf{q}) = \mathbf{g}_0(\mathbf{q}) + \Delta \mathbf{g}(\mathbf{q}) \quad (19d)$$

$$\mathbf{T}_r = \mathbf{T}_{r0} + \Delta \mathbf{T}_r \quad (19e)$$

$$\mathbf{D} = \mathbf{D}_0 + \Delta \mathbf{D}. \quad (19f)$$

In (19b)–(19f), the terms with subscript “0” and the “ Δ ” represent the nominal and uncertain terms, respectively. Choose the sliding variable as

$$\mathbf{s} = \dot{\mathbf{e}} + \mathbf{K} \mathbf{e} \quad (20)$$

where

$$\mathbf{e} = \mathbf{q} - \mathbf{q}_d \quad (20a)$$

and

$$\mathbf{K} = \text{diag}(k_1, k_2, k_3). \quad (20b)$$

The sliding mode control law can be obtained as

$$\begin{aligned} \mathbf{T}_d = & \mathbf{M}_0 \ddot{\mathbf{q}}_d + \mathbf{C}_0(\mathbf{q}, \dot{\mathbf{q}}) + \mathbf{D}_0(\mathbf{q}, \dot{\mathbf{q}}) + \mathbf{g}_0(\mathbf{q}) \\ & + \mathbf{T}_{r0} + \mathbf{u}_0 + \mathbf{u}_1 \end{aligned} \quad (21)$$

where

$$\mathbf{u}_0 = -\mathbf{M}_0 \mathbf{K} \dot{\mathbf{e}} \quad (21a)$$

and

$$\mathbf{u}_1 = -\Gamma \text{sign} \left(\left[\mathbf{s}^T \mathbf{M}_0^{-1} \right]^T \right). \quad (21b)$$

In (21b), $\Gamma = \text{diag}(\gamma_1, \gamma_2, \gamma_3)$ and γ_1 – γ_3 are constants. For the spherical motor dynamic model, the control law guarantees that the tracking error converges to zero in finite time [18].

Fig. 10 shows the control diagram of the spherical motor and the controlled responses with the sliding mode controller (21) were simulated for tracking the motion states, as shown in Fig. 8. In the simulation, 10% model errors in the rotor mass m , centroid height h_z , and rotor moment of inertia (I_{xx} , I_{yy} , I_{zz}) were added.

The controlled responses are presented in Fig. 11, which demonstrates the Euler angle tracking accuracies and the current inputs calculated by the controller. It can be seen that the

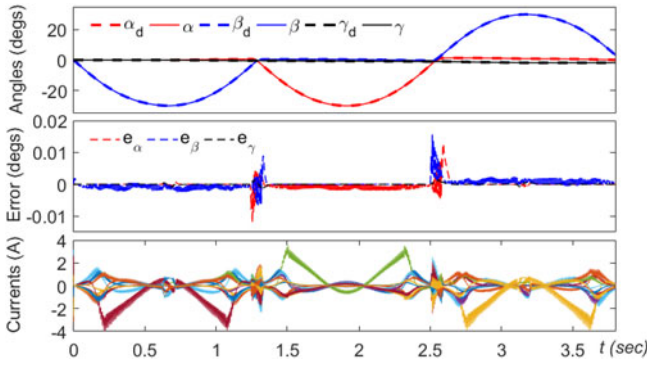


Fig. 11. Control responses (control parameters: $\mathbf{K} = \text{Diag}[150, 150, 20]$, $\mathbf{\Gamma} = \text{Diag}[0.15 \ 0.28 \ 0.05]$).

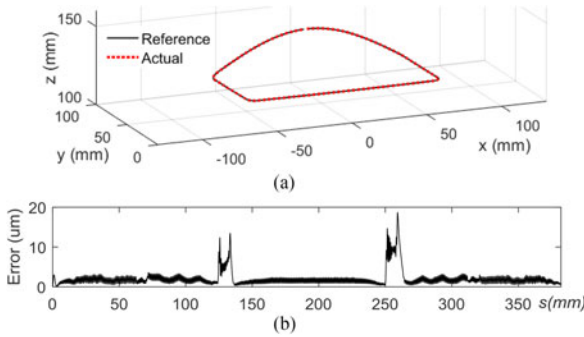


Fig. 12. Illustration of printing performance. (a) Comparison of reference and simulated printing trajectories. (b) Trajectory errors.

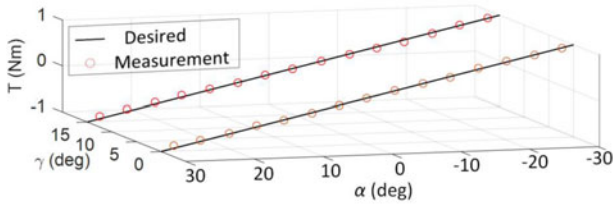


Fig. 13. Torque model validation ($\beta = 0$).

controller can effectively overcome the nonlinear dynamics and model uncertainties and track the desired trajectory quite closely with current inputs less than 4 A. The maximum tracking errors appearing at the trajectory corners (P_2 , P_3 in Fig. 5(b), where abrupt changes can be observed in the reference Euler angles in Fig. 8) are less than 0.02° . To evaluate the printing performances, the printing trajectory was estimated using the kinematic model (4a)–(4e) with the simulated motion states. Fig. 12(a) compares the reference and simulated printing trajectories and the errors are plotted in Fig. 12(b). The maximum printing error is less than $20 \mu\text{m}$.

E. Torque Model Verification

The premise of the spherical motor control requires that the torque can be accurately realized. The forward and inverse torque models (14) and (15) were experimentally validated on the test setup presented in Fig. 4(d). As shown in the figure, the

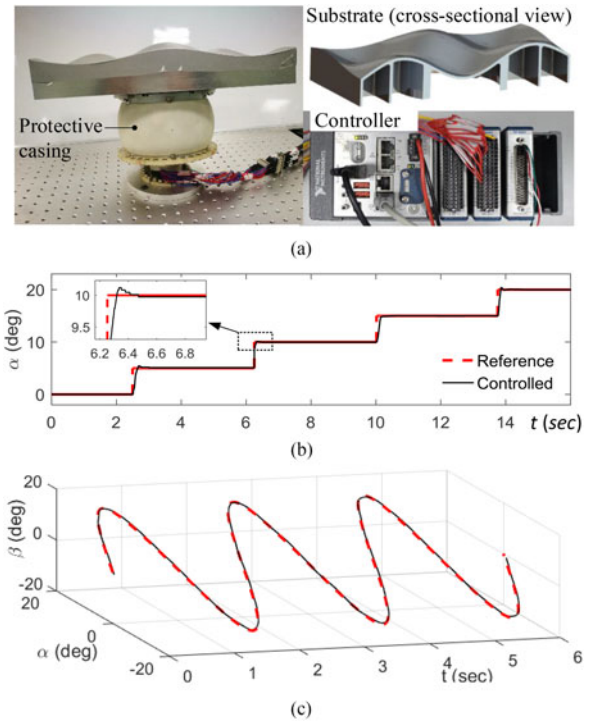


Fig. 14. Closed-loop control responses. (a) Experimental setup. (b) Step response. (c) Trajectory tracking response.

TABLE IV
CONTROL RESPONSE PARAMETERS

System parameters	Processor (CRIO-9030)	1.33 GHz, 4-G RAM
	Sampling time	5 ms
Step response (5° increment)	Settling time (5%)	0.2 s
	Overshoot	4.5%
	Steady-state error	0.04°
Tracking response (at $\gamma = 0^\circ$)	Reference inputs	$\alpha, \beta = 15 \sin(\pi t)$
	Average tracking error	0.13°

rotor is connected to a slider that can be positioned along the rotary track to lead the rotor to incline. At each orientation, the current inputs for generating an arbitrary torque can be computed with (15). The current inputs in the EMs were supplied by a linear current amplifier with a closed-loop current control implemented on an on-board circuit to assure precise and smooth current tracking. With the schematic and parameters illustrated in Fig. 4(d), the motor torque applied on the rotor can be obtained as follows:

$$T = \left(1 + \frac{l_2}{l_1}\right) T_s - T_r(\theta) + \left(m_1 l_2 + m_2 \bar{l}_2 - m_1 \bar{l}_1 \frac{l_2}{l_1}\right) g \sin \theta. \quad (22)$$

In (22), T_s is the torque measured by the load cell and T_r is the restoring torque applied by the WCR that can be computed using (17a), and the inclination angle θ can be computed using (17b). For validation, a series of desired torques were specified at different rotor orientations and the generated motor torques were recorded. Fig. 13 compares the desired and measured torques when the rotor inclined around the x axis (at $\gamma = 0^\circ$ and 15°),

$$\begin{aligned}
[\mathbf{M}] &= \begin{bmatrix} (I_1 C_\gamma^2 + I_2 S_\gamma^2) C_\beta^2 + I_3 S_\beta^2 + m h_z^2 C_\beta^2 & (I_1 - I_2) C_\gamma S_\gamma C_\beta & I_3 S_\beta \\ (I_1 - I_2) C_\gamma S_\gamma C_\beta & I_1 S_\gamma^2 + I_2 C_\gamma^2 + m h_z^2 & 0 \\ I_3 S_\beta & 0 & I_3 \end{bmatrix} \\
\mathbf{g}(\mathbf{q}) &= m g \begin{bmatrix} -C_\beta S_\alpha h_z \\ -S_\beta C_\alpha h_z \\ 0 \end{bmatrix}, \quad \mathbf{D}(\mathbf{q}, \ddot{\mathbf{x}}) = m h_z \begin{bmatrix} -C_\alpha C_\beta \ddot{Y}_C \\ C_\beta \ddot{X}_C + S_\alpha S_\beta \ddot{Y}_C \\ 0 \end{bmatrix} \\
\mathbf{C}(\mathbf{q}, \dot{\mathbf{q}}) &= \begin{bmatrix} \left[2\dot{\alpha}\dot{\gamma} C_\gamma S_\gamma C_\beta^2 + \dot{\beta}\dot{\gamma} C_\beta (S_\gamma^2 - C_\gamma^2) + \dot{\beta}^2 C_\gamma S_\gamma S_\beta \right] (I_2 - I_1) \\ -2\dot{\alpha}\dot{\beta} C_\beta S_\beta (I_1 C_\gamma^2 + I_2 S_\gamma^2) + 2\dot{\alpha}\dot{\beta} S_\beta C_\beta (I_3 - m h_z^2) + I_3 \dot{\beta}\dot{\gamma} C_\beta \\ \left(2C_\gamma S_\gamma \dot{\beta}\dot{\gamma} + \dot{\alpha}\dot{\gamma} C_\gamma^2 C_\beta - \dot{\alpha}\dot{\gamma} S_\gamma^2 C_\beta \right) (I_1 - I_2) \\ + \dot{\alpha}^2 S_\beta C_\beta (I_1 C_\gamma^2 + I_2 S_\gamma^2 + m h_z^2 - I_3) - I_3 \dot{\alpha}\dot{\gamma} C_\beta \\ \left(\dot{\alpha}^2 C_\gamma S_\gamma C_\beta^2 - 2\dot{\beta}^2 C_\gamma S_\gamma + \dot{\alpha}\dot{\beta} C_\beta S_\gamma^2 - \dot{\alpha}\dot{\beta} C_\beta C_\gamma^2 \right) (I_1 - I_2) \\ + I_3 \dot{\alpha}\dot{\beta} C_\beta \end{bmatrix}.
\end{aligned}$$

which shows good agreement. The mean absolute relative errors for the 30 sample points shown in Fig. 13 are 1.86%.

F. Closed-Loop Control Test

The closed-loop control performance of the spherical motor was experimentally tested [see setup in Fig. 14(a)] with the algorithms implemented on an NI cRIO real-time controller and an aluminum substrate mounted on top of the spherical motor. The closed-form expressions of the forward/inverse torque model led to a sampling time at 5 ms for the real-time closed-loop system. Fig. 14(b) and (c) present the controlled responses for step and sinusoidal inputs, respectively. For the step input test, an incremental of 5° change were specified on α in the range (0°–20°), and the reference and controlled responses are shown in Fig. 14(b). The key parameters for characterizing the step responses were calculated that are summarized in Table IV. The performance for tracking was also tested and evaluated. For demonstration, the controlled responses for sinusoidal commands assigned on both α and β (with $\gamma = 0^\circ$) are shown in Fig. 14(c), where the benchmarks are summarized in Table IV.

IV. CONCLUSION

A 6-DOF SMP targeted for conformal printing application was presented in this paper. Instead of using conventional serial/parallel mechanisms, the proposed SMP is based on a ball-joint-like spherical motor for delivering multi-DOF rotational motions. The concept of the SMP was validated and the performance of a prototype spherical motor was evaluated in the context of conformal printing process. The comparison between the SMP and conventional five-axis configurations shows that the SMP can provide motion with no singularities and effectively decrease motion displacements. For a typical conformal printing configuration with specified load of 7.41 kg and a printing pattern, the simulation results show that the spherical motor can perform the printing task at an accuracy of 20 μm with maximum electrical power less than 150 W. The control test

results show that the accurate orientation manipulation can be achieved, which validates the concept feasibility of the SMP for conformal printing.

APPENDIX

A. Computation of Basic Electromagnetic Components

The magnetic vector potential of a PM and an EM at point $\mathbf{R}$ can be computed using (A.1) and (A.2), respectively [16]

$$\mathbf{A}_{\text{PM}} = \frac{\mu_0}{4\pi} \int_V \frac{(\nabla \times \mathbf{M})}{|\mathbf{R} - \mathbf{R}'|} dV + \frac{\mu_0}{4\pi} \int_S \frac{(\mathbf{M} \times \mathbf{n})}{|\mathbf{R} - \mathbf{R}'|} dS \quad (\text{A.1})$$

$$\mathbf{A}_{\text{EM}} = \frac{\mu_0}{4\pi} \int_V \frac{\mathbf{J}}{|\mathbf{R} - \mathbf{R}'|} dv \quad (\text{A.2})$$

where $\mathbf{R}'$ represents variable point; $\mathbf{M}$ is the magnetization of the PM; $\mathbf{n}$ is the surface normal; and $\mathbf{J}$ is the current density.

B. Dynamic Model of the Spherical Motor

The dynamic model of the spherical motor can be derived with Lagrange formulation, which has the following form:

$$\mathbf{M}\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q}, \dot{\mathbf{q}}) + \mathbf{g}(\mathbf{q}) = \mathbf{T} - \mathbf{D}(\mathbf{q}, \ddot{\mathbf{x}}) - \mathbf{T}_r \quad (\text{A.3})$$

where the explicit expressions of the terms in the equation are shown at the top of this page.

In the equations $I_1 = I_{xx}$, $I_2 = I_{yy}$, and $I_3 = I_{zz}$, which represent the moment of inertia of the rotor/substrate; m is the rotor/substrate mass; and h_z is the distance from the centroid to the rotation center.

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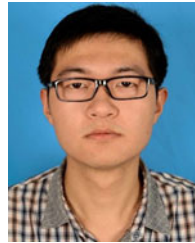
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