A Flexible Magnetically Controlled Continuum Robot Steering in the Enlarged Effective Workspace with Constraints for Retrograde Intrarenal Surgery

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Flexible magnetic continuum robots (MCRs) can be fabricated in small dimensions with great manipulability as their tips can deflect under fields, without the need for complicated mechanical structures to govern control, and it helps improve operating conditions during retrograde intrarenal surgery (RIRS). However, the limited effective workspace of an electromagnet-based magnetic navigation system (MNS) influences the practical applications. Herein, the method of steering a flexible MCR in the enlarged workspace of a common MNS for RIRS is presented. First, the field heterogeneity is parameterized to quantitatively analyze its influence on the motion of the MCR. Then, a kinematic model of the MCR is constructed, by coupling the heterogeneous-field and Cosserat-rod models, to predict its large deformation in the enlarged workspace with constraints. The model is validated with the maximum mean error of 0.53 ± 0.39 mm for the tip position in all the experiments. It is demonstrated that the effective workspace can be enlarged to 75% of the physical workspace. In addition, experiments in phantoms, which simulate two challenges during RIRS, are performed to prove its manipulability. This study enlarges the effective workspace of the MNS, which helps expand the practical application of the MCR.

1. Introduction

Kidney stones affect approximately 1 in 11 people in the United States, and the number continues to grow, owing to the modern diet and lifestyle. Retrograde intrarenal surgery (RIRS) is a common means to eliminate kidney stones. During RIRS, a flexible medical apparatus is used to extensively travel through the urinary system and then operate in the kidney. Compared with percutaneous nephrolithotomy, RIRS has a lower complication rate, blood loss, and admission time. Meanwhile, it has a higher stone-free rate than extracorporeal shock wave lithotripsy.

However, RIRS is difficult to operate using traditional apparatus, owing to the complicated anatomical features of the urinary system. First, the apparatus has to travel through the narrow and long ureter. As shown in Figure 1a, there are three regions of narrowing that occurs at the ureteropelvic junction, the crossing of the iliac vessels, and the ureterovesical junction, where the minimum diameter of the lumen is 1–2 mm or lesser, and it limits the dimension of the apparatus. Second, it requires dexterous manipulability to operate. For example, the ureterovesical junction is difficult to identify and pass through because the ureteral orifice is narrow and the angulation of the ureter is present. Moreover, stones generally exist in the multiple calyces of the kidney, and the apparatus has to go through each one to eliminate them. However, the constrained space in the kidney makes it difficult to manipulate dexterously. As a continuum medical device, traditional apparatus for RIRS, which deflects the tip by the cable embedded in the robot, has hard to reduce the dimension and has poor manipulability with the limited dimension for that it can only operate in a half-plane, and turn to another plane by rotating its proximal end. It results in long operations, considerable pain for patients, and a steep learning curve for doctors.

The continuum robots with other actuation mechanisms, such as multibackbone, pneumatic, and hydraulic, cannot be miniaturized further owing to the complicated mechanical structure used for control. Rather than embedding drive elements into the continuum robots, relocating them outside and utilizing material performance to control themselves will help reduce the dimensions of the robots. Magnetic
continuum robots (MCRs) utilize the external magnetic field to deflect the magnetic tip, which enables a structure simplification for miniaturization. Meanwhile, the field can deflect the tip directly, rather than transmitting the load through the robot body, which can reduce the load error, and we are more concerned about the motion of the tip in practical applications. Thus, the MCR has the potential to improve the operating condition during RIRS.

The magnetic navigation system (MNS) can be broadly categorized into three types, according to the source of the field, as permanent magnet, magnetic resonance scanners and electromagnets. Among these MNSs, the most electromagnet-based system utilizes several fixed electromagnets arranged in a certain configuration to generate a variable magnetic field at the center of the workspace, by adjusting the current of each electromagnet. Compared with the other two MNSs, it can quickly generate either homogeneous fields or gradient fields in a region. However, for an electromagnet-based system, the effective workspace is limited. The field is regarded as homogeneous to offer determined magnetic loads to deflect the MCR in most practical applications and researches. However, the specific homogeneous field only locates in the limited central region of the workspace, and the field heterogeneity will aggravate in the off-center region. As a result, it limits most applications that require a large workspace, such as RIRS, as shown in Figure 1a. Therefore, it is significant to study the kinematics of the MCR in the heterogeneous region to enlarge the effective operable workspace.

Several studies have modeled the MCR and analyzed its nonlinear motion considering the field heterogeneity. However, there is no validation of the model in multiple regions of the MNS with different degrees of heterogeneity, to evaluate its effective workspace, and quantitatively analyze its influence on the motion of the MCR. In addition, most studies have never analyzed the behavior of the MCR with external constraints, which is common in practical applications. Along with the field heterogeneity, the gravity and other constraints on the MCR lead to the highly nonlinear and unexpected behavior.

In this study, we explore the method of steering the MCR, instead of traditional catheters, for RIRS to improve the operating condition, which requires to enlarge the effective workspace of the electromagnet-based MNS. To this end, the field heterogeneity in the physical workspace is parameterized to quantitatively analyze its direct influence on the motion of the MCR. Then, the kinematic model of the MCR is constructed, by coupling the heterogeneous-field and Cosserat-rod models, to predict its deformation in the enlarged workspace. It can also account for the conditions with general external constraints. Experiments in phantoms, which simulate two challenges during RIRS, are performed to prove its manipulability in the constrained environment. This study aims to enlarge the effective workspace of the electromagnet-based MNS, which will help expand the practical applications of the MCR.

2. Experimental Section
2.1. Design of the MNS and the MCR
2.1.1. Design of the MNS
An MNS, which comprises some static electromagnets, can generate a controllable magnetic field. The quantity of the
electromagnets is determined by the required magnetic degree of freedom (DOF). For an untethered microrobot with a determined magnetic moment, eight electromagnets are required for five DOF control. However, only three electromagnets are required to induce three-component torque on the magnetic tip for an MCR. In this study, we choose five orthogonal electromagnets to form a symmetrical MNS for experimental validation, as shown in Figure 1b. The symmetrical configuration makes the deformation of the MCR symmetrical throughout the system. Overall, this is a simplified but adequate MNS to steer the MCR for experimental validation, and the configuration of the MNS can be optimized further to accommodate a larger physical workspace for practical applications. Details regarding the MNS are shown in Table S1, Supporting Information.

In addition to the electromagnets, we utilize a power supply, with five power amplifier modules, controlled by three DAQ (NI PCI-6229), to power each electromagnet. Two cameras are chosen to capture the motion of the MCR. Before capturing the experimental image, the Camera Calibrator in MATLAB (MATLAB R2013b, MathWorks Corporation) is used to determine the calibration parameters and correct the lens distortion of the camera. A testbed, which contains ring models and a perforated plate, is fabricated by 3D printers. Their dimension and application will be explained in detail in Section 3.2. The control algorithms are realized by using LabVIEW (LabVIEW 2012, National Instruments Corporation) and MATLAB. The physical diagram of the MNS is shown in Figure S1, Supporting Information.

2.1.2. Design of the MCR

An MCR consists of two components: an elastic rod and a magnetic tip. We choose polydimethylsiloxane (PDMS, Sylgard 184; Dow Corning Corp., Midland, MI), which has a low elastic modulus and a high Poisson ratio, to build the elastic rod. Neodymium magnets are chosen as magnetic agents in the tip as they can offer sufficient magnetic moment. The fabrication procedure and the parameters of the two components are shown in Figure 1c and Table S2, Supporting Information. The mixed solution of PDMS and the curing agent is injected into a glass tube and then cured by heating at 200 °C for 5 min. Three magnets are embedded in the tip without an interval. The diameter of an MCR in this study is 2 mm, which is determined by the magnetic tip; however, it can be fabricated with a smaller dimension if the MNS can offer a more powerful field. As we construct a simplified MNS for experimental validation, a magnetic tip with sufficient magnetic moment and dimension is required. Young’s modulus of the elastic rod can be adjusted by varying the weight ratio of the PDMS and the curing agent. Three different MCRs with Young’s modulus of 1.45, 1.25, and 0.75 MPa are fabricated in this study, respectively.

2.2. Modeling in an Enlarged Workspace

As described in the Introduction, only steering the MCR in the homogeneous region will limit the operation space to the center of the physical workspace. To enlarge the effective workspace and expand its practical applications, it is significant to study its behavior in the enlarged workspace with field heterogeneity. However, the deformation of the MCR varies nonlinearly with the input current, initial pose, extended length, and Young’s modulus in heterogeneous fields. Based on the structure and parameters of the MCR, a corresponding kinematic model, considering the field heterogeneity and other external constraints, is required. In this section, we will discuss the heterogeneous-field model and the kinematic model of the MCR, respectively.

2.2.1. Heterogeneous-Field Model

The MCR is directly actuated by the field generated by the MNS, as shown in Figure 2a. The magnetic force \( F_m \) and the magnetic torque \( T_m \) exerted on the magnetic tip are given by the following equations

\[
F_m = (m \cdot \nabla)B \quad (1)
\]

\[
T_m = m \times B \quad (2)
\]

where \( m \) is the \( 3 \times 1 \) magnetic dipole moment vector of the magnetic agent, \( \nabla \) is a gradient operator, and \( B \) is the \( 3 \times 1 \) magnetic field vector.

Assuming no electric current exists in the workspace, it will generate a divergence-free and curl-free field, and can be described by Maxwell’s equations as follows

\[
\nabla \cdot B = 0 \quad (3)
\]

\[
\nabla \times B = 0 \quad (4)
\]

Then, the magnetic gradient, which has nine components in a certain reference frame, can be represented by five components only. Equation (1) can be rearranged as

\[
F_m = \begin{bmatrix} m_x & m_y & m_z & 0 & 0 \\ 0 & m_x & 0 & m_y & m_z \\ -m_z & 0 & m_x & -m_y & m_z \end{bmatrix} \begin{bmatrix} \frac{\partial B_{x}}{\partial x} \\ \frac{\partial B_{y}}{\partial y} \\ \frac{\partial B_{z}}{\partial z} \end{bmatrix} = f(m)G \quad (5)
\]

and Equation (2) can be written in the same form as

\[
T_m = \begin{bmatrix} 0 & -m_z & m_y \\ m_z & 0 & -m_x \\ -m_y & m_x & 0 \end{bmatrix} \begin{bmatrix} B_x \\ B_y \\ B_z \end{bmatrix} = t(m)B \quad (6)
\]

where \( f(m) \) and \( t(m) \) are functions of \( m \), and contribute to the magnetic force and torque, respectively.

As shown in Figure 2a, \( m \) is correlated with the orientation of the magnetic tip; it can be represented by two angles, \( \theta \) and \( \varphi \), as follows

\[
m = \begin{bmatrix} m_x \\ m_y \\ m_z \end{bmatrix} = \begin{bmatrix} \cos \theta \sin \varphi \\ \sin \theta \sin \varphi \\ \cos \varphi \end{bmatrix} = M \quad (7)
\]

where \( M \) is the magnitude of the magnetic moment \( m \), \( c \) and \( s \) indicate \( \cos \) and \( \sin \), respectively. Thus, \( f(m) \) and \( t(m) \) can be rewritten as follows.
where \( \text{dir} \) represents the orientation of the tip.

Consequently, combining Equation (5), (6), (8), and (9), the external magnetic load \( \mathbf{w} \) on a magnetic tip can be derived as follows

\[
\mathbf{w} = \begin{bmatrix}
c \theta s \varphi & s \theta s \varphi & c \varphi & 0 & 0 \\
-\varphi & 0 & s \theta s \varphi & c \varphi & 0 \\
-c \varphi & 0 & c \theta s \varphi & -c \varphi & s \theta s \varphi \\
0 & -c \varphi & 0 & s \theta s \varphi & c \varphi \\
\end{bmatrix} \mathbf{M}
\]

(8)

\[
\mathbf{t} = \begin{bmatrix}0 & -\varphi & 0 & s \theta s \varphi & c \varphi & 0 \\
\varphi & 0 & -\varphi & s \theta s \varphi & c \varphi & 0 \\
-c \varphi & 0 & \varphi & -c \varphi & s \theta s \varphi & 0 \\
0 & -\varphi & 0 & c \varphi & 0 & s \theta s \varphi \\
\end{bmatrix} \mathbf{M}
\]

(9)

where \( \mathbf{O} \) is an appropriately sized matrix of zero. It shows that we need eight magnetic DOF to control six mechanical DOF. However, we only utilize the magnetic torque to deflect the MCR, and the magnetic force induced by the field heterogeneity is considered to calibrate the model. Thus, five electromagnets contained in the MNS are sufficient to deflect the MCR.

In the workspace of the MNS, the center of the field can be regarded as homogeneous, thus \( \mathbf{B} \) and \( \mathbf{G} \) in this region are invariable. However, it is inapplicable in the off-center region, where \( \mathbf{B} \) and \( \mathbf{G} \) may vary rapidly. It is proper to regard the magnetic field as heterogeneous and determine the field data according to the specific position.

The magnetic field in the workspace is proportional to the current (details are available in Figure S2, Supporting Information); thus, it can be determined as

\[
\mathbf{B}(\mathbf{p}_c) = \hat{\mathbf{B}}(\mathbf{p}_c) \mathbf{I}
\]

(11)

where \( \mathbf{p}_c \) is the position of the control point, \( \hat{\mathbf{B}}(\mathbf{p}_c) \) is the current normalized field at the control point, and \( \mathbf{I} \) is the input current. Specifically, if there are \( N \) electromagnets, then the \( \hat{\mathbf{B}}(\mathbf{p}_c) \) is a \( 3 \times N \) matrix and \( \mathbf{I} \) is an \( N \times 1 \) matrix. Then \( \mathbf{I} \) can be calculated by the expression as follows

\[
\mathbf{I} = \hat{\mathbf{B}}(\mathbf{p}_c) \dagger \mathbf{B}(\mathbf{p}_c)
\]

(12)

where \( \mathbf{B}(\mathbf{p}_c) \) is the desired field and \( \dagger \) is the symbol of the pseudoinverse. Then, the field \( \mathbf{B}(\mathbf{p}_c) \) and gradient \( \mathbf{G}(\mathbf{p}_c) \) around the tip can be derived as follows

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**Figure 2.** Schematic for the coupled model. a) Load condition of the MCR in a heterogeneous magnetic field. The heterogeneous field directly deflects the tip, and constraints on the elastic rod influence internal force along the arc length. b) Method to acquire the magnetic field data in the whole workspace using an FE model.
where \( \mathbf{p}(t) \) is the actual position of the tip, and \( \dot{\mathbf{B}}(p) \) and \( \dot{\mathbf{G}}(p) \) are current normalized field and gradient, respectively.

As shown in Figure 2b, \( \mathbf{B} \) and \( \mathbf{G} \) are acquired by the finite element (FE) model. The side length of the cubic workspace is divided by 15 points, and thus the cubic workspace is divided into 4096 cubes with 4913 points. On powering one electromagnet with 1 A, \( \hat{\mathbf{b}} \) and \( \hat{\mathbf{g}} \) on those points can be obtained, and the data for the other electromagnets can be rapidly transformed using the data from the first owing to geometric symmetry. And the data on arbitrary points in the workspace can be calculated using linear interpolation. The field is calibrated by using a gauss meter to measure the value on determined points of the physical system with the maximum intensive error of 3.94% (see more details for calibration in Figure S2, Supporting Information).

Eventually, combing Equation (10) and (13), the external load \( \mathbf{w} \) exerted on the tip can be written as follows

\[
\mathbf{w} = M \begin{bmatrix}
    \mathbf{i}_d(\text{dir}) & \mathbf{O} \\
    \mathbf{O} & f_d(\text{dir})
\end{bmatrix} \begin{bmatrix}
    \dot{\mathbf{B}}(p) \\
    \dot{\mathbf{G}}(p)
\end{bmatrix} \mathbf{I}
\]

(14)

The magnetic load on the MCR can be derived according to the input current and the pose of the tip.

The heterogeneous field will vary nonlinearly in the off-center region, and cause an unexpected magnetic load. Considering the spatially varying fields, the model can map the field around the tip and calculate the magnetic load accurately. This helps enlarge the effective workspace of the MNS, not only limit to the center region.

2.2.2. Kinematic Model

The Cosserat rod theory can describe the deformation of a long slender object. It assumes that the rod is made up of rigid particles attached to a coordinate frame so that the internal normal and shear stresses can be calculated when the particles translate and rotate along the object’s arc length. Therefore, in general, it can solve large deformation problems of an elastic rod with variations in stiffness, cross section, body loading, and point loading. In this section, we utilize the Cosserat rod theory to construct a kinematic model of the MCR in heterogeneous fields with external constraints. Ordinary differential equations (ODEs) are derived from the rod kinematics, equilibrium equations, and constitutive laws.\(^{[14]}\)

For analysis, the MCR can be divided into two parts, the elastic rod and a rigid tip, as shown in Figure 2a. The elastic rod is a passive part that follows the rigid tip, and it will suffer contact constraints during operation. The rigid tip is actuated by the field directly.

The shape of an elastic rod can be described by \( \mathbf{g}(s) \in \text{SE}(3) \), the transformation matrix of the rigid coordinates along arc length \( s \), as follows

\[
\mathbf{g}(s) = \begin{bmatrix}
    \mathbf{R}(s) & \mathbf{p}(s) \\
    \mathbf{0} & 1
\end{bmatrix}
\]

(15)

where \( \mathbf{p}(s) \in \mathbb{R}^3 \) and \( \mathbf{R}(s) \in \text{SO}(3) \) are the position matrix and the orientation matrix, respectively. Specifically, the derivative of the \( \mathbf{p}(s) \) and \( \mathbf{R}(s) \) could be derived as follows

\[
\mathbf{p}(s) = \mathbf{R}(s)\mathbf{v}(s) \\
\mathbf{R}(s) = \mathbf{R}(s)\mathbf{u}(s)
\]

(16)

where \( \mathbf{v}(s) \) and \( \mathbf{u}(s) \) are the linear and angular rate of change in \( \mathbf{g}(s) \), respectively, and obey the constitutive laws

\[
\mathbf{v}(s) = \mathbf{v}^c(s) + \mathbf{K}_{\text{st}}(s)\mathbf{R}(s)^T\mathbf{f}(s) \\
\mathbf{u}(s) = \mathbf{u}^c(s) + \mathbf{K}_{\text{st}}^{-1}(s)\mathbf{R}(s)^T\mathbf{t}(s) \\
\mathbf{K}_{\text{st}}(s) = \text{diag}(\mathbf{G}(s), \mathbf{G}(s), \mathbf{E}(s)) \\
\mathbf{K}_{\text{st}}^{-1}(s) = \text{diag}(\mathbf{E}(s), \mathbf{E}_p(s), \mathbf{E}_{zz}(s))
\]

(17)

\( \mathbf{K}_{\text{st}}(s) \) and \( \mathbf{K}_{\text{st}}^{-1}(s) \) are the stiffness matrices for shear and extension, and bending and torsion, respectively. \( \mathbf{G}(s) \) and \( \mathbf{E}(s) \) are the shear modulus and Young’s modulus, respectively; \( \mathbf{A}(s) \) is the cross-sectional area; \( \mathbf{I}_{xx} \) and \( \mathbf{I}_{yy} \) are the second moments of the area; \( \mathbf{I}_{zz} \) is the polar moment of inertia. \( \mathbf{v}^c(s) \) and \( \mathbf{u}^c(s) \) are the initial value of linear and angular rates.

Then, considering the load exerted on the MCR, the equilibrium equations can be expressed as

\[
\mathbf{f}(s) = -\mathbf{f}_e(s) \\
\mathbf{t}(s) = -\mathbf{p}(s) \times \mathbf{f}(s)
\]

(18)

where \( \mathbf{f}(s) \) and \( \mathbf{t}(s) \) are the internal force and torque, respectively, and \( \mathbf{f}_e(s) \) is the applied force distribution of \( \Delta s \), e.g., the gravity. Therefore, ODEs for the transformation of the flexible component of the MCR can be expressed by Equation (16) and (18).

If there exist external loads or position constraints on the elastic rod, as shown in the inset of Figure 2a, then, \( \mathbf{f}(s) \) and \( \mathbf{t}(s) \) at the load point \( s = \sigma \) can be calculated as follows

\[
\mathbf{f}(\sigma^+) = \mathbf{f}(\sigma^-) + \mathbf{F}_e \\
\mathbf{t}(\sigma^+) = \mathbf{t}(\sigma^-) + \mathbf{T}_e + \mathbf{T}_F
\]

(19)

where \( \sigma^- \) and \( \sigma^+ \) are two sides of the load point that close to the distal end and proximal end at arc length \( \sigma \), respectively. \( \mathbf{F}_e \) and \( \mathbf{T}_e \) are the external force and torque, respectively, and \( \mathbf{T}_F \) is the torque induced by \( \mathbf{F}_e \).

Specifically, if there exist determined external loads, it can be solved by adjusting the external loads in Equation (18). As for the situations with position constraints along the elastic rod, by adding constraint boundary conditions, the ODEs can be regarded as a multipoint boundary problem with unknown parameters, which represent the constraint loads. And the amount of the points with constraints determines the amount that the MCR is divided into. As shown in the inset of Figure 2a and Equation (19), the boundary conditions of the two sides at a point with constraints, \( \mathbf{w}(\sigma^+) \) and \( \mathbf{w}(\sigma^-) \), are different, and it satisfies the load relationship as follows

\[
\mathbf{w}(\sigma^+) = \mathbf{w}(\sigma^-) + \mathbf{w}_c
\]

(20)

where \( \mathbf{w}_c \) is the constraint load. For example, if there is no constraint on a rod, then the ODEs are 12 sets and 12 boundary conditions need to be determined as follows.
where \( \text{pro} \) and \( \text{dis} \) represent the point at the proximal end and distal end of the elastic rod. If there is a position constraint on the point \( p(\sigma) \), then the rod can be divided into two parts according to it. Thus, there are 24 sets of ODEs and three unknown constraint loads. Apart from the aforementioned 12 boundary conditions, additional 15 sets are required to be defined as follows

\[
\begin{align*}
p(\sigma^+) &= p(\sigma^-) \\
R(\sigma^+) &= R(\sigma^-) \\
t(\sigma^+) &= t(\sigma^-) \\
p(\sigma^+) &= \sigma \\
f(\sigma^+) &= f(\sigma^-) + f_c
\end{align*}
\]

where \( f_c \) is the constraint force at \( p(\sigma) \).

Different from the elastic rod, the kinematics of the rigid tip differs. Assuming the state of the distal end of the elastic rod can be described as follows

\[
x_{\text{dis}} = \begin{bmatrix} p_{\text{dis}} \\ R_{\text{dis}} \\ f_{\text{dis}} \end{bmatrix}
\]

then the pose of the tip along the arc length can be expressed by

\[
\begin{align*}
p(s) &= p_{\text{dis}} + (s-l_e)R_{\text{dis}}v \\
R(s) &= R_{\text{dis}}
\end{align*}
\]

where \( l_e \) is the length of the elastic rod.

In this study, assuming no external force and torque are applied to the tip except for gravity, so the internal force and torque evolving along the tip do not be considered. However, the load should be analyzed as boundary conditions as follows

\[
\begin{align*}
f_{\text{dis}} &= -(F_m + f_c) \\
t_{\text{dis}} &= -(T_m + 0.5l_e[R_{\text{dis}}v] \times f_{\text{dis}})
\end{align*}
\]

where \( F_m \) and \( T_m \) are magnetic force and torque, respectively, and \( l_e \) is the length of the tip.

Consequently, the kinematics of the elastic rod can be expressed by Equation (16) and (18), and that of the rigid tip directly actuated by the field can be expressed by Equation (24) and (25). This kinematic model can not only predict the deformation of the MCR in heterogeneous fields but also handle situations with common constraints, which is of more practical significance.

2.2.3. Control Algorithm

In this section, we introduce a linear incremental approximation algorithm to solve the large deformation problem of the MCR in heterogeneous fields. In addition, the control algorithm for the tip trajectory control is also explained.

The ODEs derived from the kinematic model of the MCR can be solved with the bvp5c module in MATLAB, which is a finite difference code that implements the four-stage Lobatto IIIa formula. In a homogenous field, the intensity and direction of the field around the tip are invariable, so that it can be easily solved with determined parameters concerning the field, regardless of what deformation of the MCR is. However, it differs in a heterogeneous field, and three reasons why the solution cannot be solved directly are explained later. First, the magnetic torques exerted on the tip of the MCR, at the stable state, are different from the initial calculated state because the field around the tip and pose of tip both vary during deflection. Second, due to the heterogeneity, the local field around the tip is not homogeneous and induces a variable extra magnetic force on the tip which cannot be eliminated in most situations. At last, the magnetic load, calculated at the initial state, is generally large and causes excessive deformation and nonconvergence in a region with dramatic field variation. Therefore, to derive a precise solution that describes the large deformation of the MCR in a heterogeneous field, these details should be considered, and the states of the local field and the MCR are supposed to be iterated until it approaches a stable state.

To solve it, a linear incremental approximation algorithm is introduced. First, rather than directly using the actual input current \( I \) calculated by Equation (12), we iterate the current linearly by step as follows

\[
I_i = I \times i/N
\]

where \( N \) is the number of the steps, and \( i = 1, 2, ..., N \), and then compute the extra field force exerted on the tip except for the only torque as shown in (13). When the current reaches the expected value, the iteration continues with that until the divergence between the tip positions of the last two iterations is less than a threshold. In this way, a large deformation is decomposed into multiple small deformations and the nonconvergence caused by the divergence of the load between the initial state and stable state can be avoided. The detail of this algorithm can be seen in Algorithm 1, Supporting Information.

The coupled model can serve as a feedforward in open-loop control for a practical motion task. For example, for the tip trajectory control, the input current can be derived by the model according to the desired trajectory with improved accuracy. In this study, we only focus on the motion of the tip in the \( X-Y \) plane, and thus the trajectory can be represented several points as follows

\[
p = [r, \theta]
\]

where \( r \) is the distance to the origin and \( \theta \) is the orientation in the \( X-Y \) plane. Then, the error can be calculated by

\[
E_i = p_i^D - p_i^M, \quad i = 1, 2, ..., n
\]

where \( p_i^D \), the desired position of the selected points, can be calculated according to a reference point \( p_i^D \); \( p_i^M \) is the position, calculated by coupled model according to the estimated input current. Then, the actual current will be calculated using an approaching iteration algorithm to satisfy \( E_i < [\text{threshold}_r, \text{threshold}_\theta] \). The detail of this algorithm can be seen in Algorithm 2, Supporting Information. The results concerning the tip trajectory control will be introduced in Section 3.2.2.
3. Results and Discussion

3.1. Evaluation of the Field Heterogeneity

To evaluate the heterogeneity of the magnetic field generated by the system, we first powered two opposite electromagnets with 1 and $-1$ A, respectively, resulting in a relatively homogeneous field toward the positive $X$-axis in the workspace, as shown in Figure 3a,b, the results simulated by COMSOL Multiphysics suite v.5.0 (COMSOL AB, Stockholm, Sweden). Apart from the most heterogeneity index computed by intensity deviation,$^{[32]}$ we also selected angular deviation as another parameter, which will also determine the motion deviation of the MCR. As a result, the volume proportion of the region where the maximum field intensity deviation rate below 10% and the maximum angular deviation below $2^\circ$ to the whole workspace were 11.63% and 9.75%, respectively. However, for stable magnetic manipulation, the enveloped region was selected as an effective homogeneous workspace rather than this irregular region. In this way, the effective homogeneous region can be evaluated by the diameter proportions of the enveloped circle, which were 22.48% and 18.71%, respectively. The proportions will vary if the field direction changes, as shown in Figure 3c and Figure S3, Supporting Information. Evidently, the homogeneous region in an MNS is limited, and only operating in this region will restrict practical applications.

To evaluate the influence of the heterogeneous field on the deformation of the MCR, an experiment with two control modes, Mode Homo and Mode Hetero, was set here. Mode Homo ignored the heterogeneity and only varied the magnetic field at the center point of the workspace, by varying the current to control the deflection of the MCR. In contrast, Mode Hetero shifts the position of the control point, according to the initial position of the tip, to reduce the influence of the heterogeneity. Specifically, as shown in the inset of Figure 3d, four regions with a diameter of 30 mm, O, A, B, C, respectively, were selected as deformation regions, and the green circle represents region A. Then, the MCR was deflected with a certain extended length.

![Figure 3](https://example.com/figure3.png)

**Figure 3.** Evaluation of the field heterogeneity. a,b) Simulation results of the field that powering the opposite electromagnets with 1 and $-1$ A, which show the intensity deviation and angular deviation to the center point, respectively. c) The proportion of the homogeneous region with different field directions. d) Illustration for the experiment that evaluating the influence of the heterogeneity on the motion of the MCR. The coordinates of center points in four regions, O, A, B, and C, are (0, 0, 0), (–10, 10, 0), (–10, 0, 0), and (0, 10, 0), respectively. The diameter of each region is 30 mm. e) The angular relationship between the tip and the field in Mode Homo and Mode Hetero. f) The individual relationship at four regions in Mode Homo. g–i) Three parameters of the field heterogeneity in four regions in Mode Homo and Mode Hetero, respectively.
in those regions, and the angular relationship between the tip and the field was recorded. Young’s modulus of the MCR was 1.25 MPa, and the field intensity and direction relative to the initial orientation of the tip at the control point were 3.65 mT and -120° to 120°, respectively.

As experimental results show (Figure 3e,f), in Mode Homo, the relationship in four regions has a larger mean deviation of 1.71° than that of 0.81° in Mode Hetero, although the mean deviation of the deformation in a single region is 0.28° with three repeated measurements. Furthermore, as can be seen in the purple circle region, when the field at the control point heads to the initial orientation of the tip, it will also deflect at region B and C in Mode Homo because the field directions at the control point and tip orientation are different, which results in an offset from the origin in Mode Homo. However, it can be avoided in Mode Hetero, as shown in Figure S3, Supporting Information. Therefore, it demonstrates that the field heterogeneity will influence the deformation and reduce the control accuracy of the MCR.

To quantify the influence of the heterogeneity on the motion of the MCR in a region, three parameters, \( \epsilon_1, \phi_A, \) and \( \phi_B, \) were defined to help analyze as follows

\[
\epsilon_1 = \frac{1}{n_{B_k} B_k} \sum_{\theta_k} \left( \frac{1}{n_p} \sum_p B(p, \theta_k) - B_k \right) \times 100% \tag{29}
\]

\[
\phi_A = \frac{1}{n_{\theta_k}} \sum_{\theta_k} \left( \frac{1}{n_p} \sum_p \theta(p, \theta_k) - \theta_k \right) \tag{30}
\]

\[
\phi_B = \frac{1}{2n_{\theta_k}} \sum_{\theta_k} \left( \max(\theta(p, \theta_k)) - \min(\theta(p, \theta_k)) \right) \tag{31}
\]

where \( B_k \) and \( \theta_k \) are the intensity and direction of the field at the control point, and \( B(p, \theta_k) \) and \( \theta(p, \theta_k) \) are those at sampling points in one region. \( n_p \) and \( n_{\theta_k} \) are the amounts of the sampling points and the sampling field directions, respectively. As a result, \( \epsilon_1 \) and \( \phi_A \) indicate the mean deviation rate of field intensity and the mean deviation of the field direction to the control point, respectively. \( \phi_B \) indicates the mean maximum angular deviation in a region. The three parameters \( \epsilon_1, \phi_A, \) and \( \phi_B \) reflect the heterogeneity of the field intensity, the symmetry of the field direction, and the dispersion of the field direction in a region, respectively.

The three parameters, as shown in Figure 3g–i, can help explain the experimental results. In Mode Homo, the control point in the four regions was always the point O. \( \phi_A \) of the regions O, A, B, C are 0°, 0°, 1.0°, and -1.0°, respectively. The asymmetrical field in regions B and C makes the deformation asymmetrical, as the result shown in Figure 3f. In region A, it has larger \( \epsilon_1 \) and \( \phi_A \) than that in region O, which reflects that the field spatial variation in region A is larger, and the deformation relationship deviates with region O. In Mode Hetero, the control points shift to point A, B, and C, respectively, when deflecting in their regions. \( \epsilon_1 \) and \( \phi_A \) have reduced significantly compared with that in Mode Homo. Despite \( \phi_B \) in Mode Hetero has increased, overall it makes the four relationships more symmetrical and coincident than that in Mode Homo.

Although the influence of the heterogeneity can be reduced by shifting the control point as theoretical analysis and experiments show, it will still exist and strengthen with the deviation from the center of the workspace and the enlargement of the deformation region. Thus, to enlarge the effective workspace in practical applications, it requires to consider the influence of the heterogeneity on the motion of the MCR.

### 3.2. Experimental Validation of the Coupled Model in the Enlarged Workspace

Considering the extra magnetic force and the variation of the magnetic torque caused by the field heterogeneity, the coupled model provides a precise deformation prediction, and it can also account for the situation with external constraints. In this section, we performed experiments to validate the model by comparing the deformation of the MCR derived from the model and experiments in the following scenarios: 1) deflection in a single direction with linearly varying input current, 2) deflection in different directions with a defined current, 3) deflection in different regions of the workspace, and 4) deflection with external constraints.

#### 3.2.1. Deflection in a Single Direction

As shown in Figure 4a, the MCR was vertically placed at the center of the MNS, and the extended lengths were 15, 20, and 25 mm, respectively. The positions of the proximal end and the control point were (0, 0, 20) and (0, 0, 0), respectively. A commercial microcamera was used to capture the motion of the MCR with an image processing algorithm.

To verify the coupled model, we deflected three MCRs with different stiffness and extended length in a single direction, with a linearly varying input current, and recorded the deflection of the tip. Each measurement was repeated nine times to reduce the errors caused by deviations from the length that stretch out, and relative initial point to the system. In addition, another nine measurements, deflecting in the opposite direction, were set to eliminate the origin offset. As shown in Figure 4b–d, the results from the coupled model have a significant match with the experimental results, and the mean error of 0.53 ± 0.39 mm is well below the diameter of the MCR. The results show high repeatability with a mean standard deviation of 0.29 mm.

For comparison, we ignore the heterogeneous-field model in the theoretical calculation as Mode Homo, and the results of them are shown in Figure S4, Supporting Information. One heterogeneous-field model-free result \((E = 0.75 \text{ MPa})\) and one typical comparison of the two models \((E = 0.75 \text{ MPa}; L = 20 \text{ mm})\) are shown in Figure 4e,f. There is a near-linear variation with current occurring in a small deformation region (blue region) in both groups, where the heterogeneity has an insignificant impact on the motion of the MCR and can be neglected. However, it is not the case in the large deformation region. As shown in Figure 4f, the deviation of the model in Mode Homo has increased rapidly in the off-center heterogeneous region and shows the same tendency with \( \epsilon_1 \), which reflects the heterogeneity of the field intensity. In that region, the field heterogeneity, which causes a varying magnetic torque and induces an extra magnetic force, evidently influenced the motion of the MCR. In addition, as the results show, the diameter
proportion of the homogeneous region (blue region) is 20% (diameter of 16 mm), which is comparable with that of the enveloped homogeneous region in the simulation result in Figure 3c.

3.2.2. Deflection in Different Directions

Due to the field heterogeneity, the deflection of the MCR varies in different directions, although the field intensity remains the same at the center of the MNS. As shown in Figure 5a and Figure S5, Supporting Information, according to the coupled model, we can develop a tip position map with different input current, deflection direction, and extended length. According to the top view of the map (Figure 5a), the deflection of the tip varies as the field direction changes, and it reaches the lowest point when the field heading to the diagonal of the workspace. In addition, this variation aggravates in the off-center region. As the results show, the diameter of the region, where can ignore this variation, is smaller than 12 mm, which is less than 15% of the physical workspace and matches the lowest value of the $R_{\text{Dia,Exp}}$ in Figure 3c.

To verify the coupled model, it is necessary to compare the deformation with the experiments in different directions. As shown in Figure 5b,c, deflecting the MCR in multiple directions with Young’s modulus of 1.25 MPa under three fields, the results from model and experiments show a significant match with a mean tip position error of 0.34 ± 0.30 mm and a mean deflection direction error of 1.9 ± 1.4°.

Utilizing this model, a tip trajectory control experiment can be accomplished with improved accuracy, as shown in Figure 5d,e (see Video 1, Supporting Information). For comparison, we set a control group in Mode Homo, which varies the input current to change the field direction at the control point, but the field intensive will remain unchanged. In this way, the field was assumed to be homogeneous, and thus the tip was expected to head toward the field direction in the X–Y plane and the deflection of the tip will remain unchanged. However, in this mode, the maximum position errors of the control group were 1.61, 2.64, and 1.21 mm, respectively, and the mean position errors were 0.45 ± 0.35, 0.99 ± 0.71, and 0.68 ± 0.29 mm, respectively. In addition, it obviously diverged the deflection direction. The error increased significantly in the off-center region because the heterogeneity aggravated. However, with the coupled model in Mode Hetero, the mean position errors were reduced to 0.23 ± 0.14, 0.37 ± 0.21, and 0.30 ± 0.15 mm, which were 50.4%, 37.1%, and 44.7% of that in Mode Homo, respectively, as shown in the test group in Figure 5e.

3.2.3. Deflection in Different Regions

In addition to predicting the tip position in a heterogeneous field with high accuracy, the model can reconstruct the shape of the MCR in an enlarged workspace. An MCR with 30 mm in length was placed horizontally in three regions of the MNS with a diameter of 30 mm and deflected by the field in Mode Homo. $\epsilon_1$ of the three regions were 12.5%, 3.7%, and 12.5%, respectively, and $\phi_B$ of that were 20.3°, 8.6°, and 20.3°. As shown in Figure 6a, the field heterogeneity varied the deformations in different regions, but all of them can be predicted by the coupled
model with a mean error of $0.25 \pm 0.20$, $0.21 \pm 0.13$, and $0.19 \pm 0.12$ mm, respectively. Each deflection in the same region was repeated three times, and the positions of ten equidistant points along the arc length were recorded.

As the result shows, in this experiment, the MCR can be operated in a region with a diameter of 60 mm (the blue dotted region), which is 75% of the physical workspace, and the model can predict the deformation of the MCR accurately in all this region. In this way, the effective workspace can be enlarged rather than the only center of the physical workspace. In fact, the model can also predict the deformation of the MCR out of this region, but the severe field heterogeneity will influence the effective motion, as shown in the right result in Figure 6a.

### 3.2.4. Deflection with Constraints

In practical applications, external constraints and loads make control complicated and unpredictable. Few related works provide an accurate prediction of the deformation of an MCR with constraints. In this work, experiments were set to verify the accuracy of the coupled model with constraints. Rings models, with 35, 37.5, and 40 mm in height, were fabricated by 3D printers, and the position and orientation of rings can be adjusted on a

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**Figure 5.** Validation of the model with the deflection in different directions. a) The top view of the tip position map calculated by the coupled model. b) The illustration for the validation experiment. c) Comparison between the experimental results and the theoretical results. d) Trajectory control of the tip. The test group (the lower row) is controlled by the coupled model in Mode Hetero, but it ignores the heterogeneity in the control group in Mode Homo (the upper row). e) Position errors during each experiment. Each trajectory is repeated three times. The transparent lines plot the mean errors in each group.
perforated plate. The diameter and width of the rings were both 4 mm, while the diameter of the initial ring was 2.2 mm, which was a bit larger than that of the MCR. During the experiments, the magnetic field was controlled according to the position of the tip, while the MCR was pulled/pushed manually at a slow speed. During the motion, the elastic rod of the MCR was subject to the constraints of the rings, in addition to gravity.

The result of steering in the X–Z plane with position constraints can be seen in Figure 6b–d. There were horizontal distances of 16 mm and a vertical distance of 2.5 mm between neighboring rings. Three typical crossing moments, i, ii, and iii, were captured, respectively, and the deformations of them can be obtained by image processing. In the actual experiment, at moment i, there was no constraint, while at moments ii and iii, there was a position constraint and three position constraints, respectively. According to the relationship of the MCR and rings, the shapes of the MCR were theoretically analyzed by the coupled model. Then, the accuracy of the model was evaluated by the position deviation of the points, 3 mm apart, along arc length. As a result, the mean errors of the three moments were 0.29 ± 0.09, 0.26 ± 0.12, and 0.31 ± 0.19 mm, respectively.

In addition, we performed another experiment of steering the MCR in the X–Y plane. The results can be seen in Figure S6, Supporting Information, and it shows comparable performance compared with that in the X–Z plane.

However, in practical applications, it requires knowledge of the body-robot contact to solve the situations with constraints using this model. But it can be applied to virtual devices to train operators, which can help improve surgical efficiency and reduces X-ray irradiation time. In that scenario, the knowledge of the body-robot contact is reachable. As for the operation in vivo, it may rely on the development of the localization systems and physiological sensors, to offer real-time position and load information along with a miniaturized MCR.

### 3.3. Steering in Phantoms

For RIRS, a flexible medical apparatus is required to extensively travel through the narrow and long urinary system. The traditional apparatus has poor manipulability owing to its limited dimension; furthermore, it results in a long operation,
considerable pain for patients, and a steep learning curve for doctors. However, MCR has the potential to improve the operating conditions owing to its small dimension and dexterous manipulability. Here, we performed experiments in phantoms with a manual magnetic mode (“man-in-the-loop”) to prove its manipulability in several main sites of the urinary system. Specifically, the robot is inserted or pulled out manually, and the deflection of the robot is controlled by inputting the control position, field intensive, and field direction using a joystick. However, the input information is determined by the operator.

3.3.1. Steering through the Narrow Rings

As per the description in the Introduction, during RIRS, there are three regions of narrowing, where the minimum diameter of the lumen is 1–2 mm or lesser. And steering the apparatus through the ureterovesical junction is one main challenge during RIRS because the ureteral orifice is narrow and the angulation of the ureter is present. The apparatus has to be able to dexterously deflect to identify and pass through the narrow orifice. To prove the manipulability of the MCR, we steered it through multiple narrow rings with a diameter of 4 mm, which was only a bit larger than the size of the MCR. Figure 7a shows the process steering the MCR to pass through two narrow rings on the two sides, which simulated the two ureteral orifices at the ureterovesical junction. The deflection angle of the neighboring rings was 18.4°. Apart from selective motion, we also steered the MCR to achieve 3D and backward motion, as shown in Figure 7b,c. In 3D motion, rings were set at different heights and orientations. There was a maximum altitude difference of 5 mm between rings. Furthermore, in the X–Y plane, the last ring eventually turned 90° counterclockwise. The backward motion was performed here because it is always difficult but significant for a continuum robot because the targets are not always located in the front (see Video 2, Supporting Information, for more details). The experiment here proves that the MCR can dexterously pass through narrow rings with different configurations, and it is a significant ability during practical applications, such as to identify and pass through the narrow orifice during RIRS. Moreover, in this experiment, the rings were located in a region with a diameter of 60 mm; ε₁ and φ_B in this region were 11.2% and 48.4°, respectively, which proves the controllability of the MCR in an enlarged workspace with the field heterogeneity and external constraints.

3.3.2. Steering in the Phantom of the Kidney

Another challenge during RIRS is encountered when the apparatus is steered in the kidney and inserted into multiple calyxes. The space in the kidney in which the apparatus can operate is restricted; therefore, it should be able to dexterously deflect in the limited space. Here, we built a phantom of the kidney with the dimensions of 85 × 54 × 19 mm, which were the comparable dimensions of a real kidney, as shown in Figure 8a. The phantom represented several major and minor calyxes linked to the kidney pelvies and seven renal papillae with a minimum diameter of 2 mm. During the experiment, the model was filled with water to simulate the environment in the kidney. Eventually, we controlled the MCR to pass through most calyxes and reached the renal papillae, as shown in Figure 8b, which proves the

![Figure 7](https://www.advancedsciencenews.com)
manipulability of the MCR to steer in a restrictive space (see Video 3, Supporting Information, for more details).

4. Conclusion

In this study, we explore the method of steering the MCR, instead of traditional catheters, for RIRS to improve the operating condition. However, one of the limitations to the fixed electromagnetic system is that it cannot generate a homogenous field in a large proportion region as a Helmholtz coil-based system does. The homogenous region locates in the center of the workspace, which is below 15% of the whole physical workspace in our system, and this proportion is not sufficient for surgery such as RIRS, which requires the traversal of a long distance to the region of interest from the origin, and the region of interest is not in the center of the body. Thus, instead of enlarging the homogenous region by optimizing system structure, we analyze the kinematics of the MCR in the enlarged region with field heterogeneity in this study, to enlarge the effective workspace.

We first evaluated the field heterogeneity of an MNS and demonstrated that the homogenous region in a common MNS is not sufficiently large for practical applications such as RIRS. Then, by quantifying the heterogeneity with multiple parameters, we analyzed the influence on the motion of the MCR. For example, an asymmetrical field makes the deformation asymmetrical, and causes an origin offset; in the enveloped region of the homogenous field, MCR can deflect uniformly in different directions. By coupling the heterogeneous-field and Cosserat-rod models, the kinematic model of the MCR in the enlarged workspace was constructed. And this model can predict the complicated nonlinear behavior of the MCR accurately in heterogeneous fields with external constraints, with the maximum error of 0.53 ± 0.39 mm in multiple experiments. It has also been studied in the region of the system with a diameter of 60 mm, where it has large field variation. The results demonstrate the effectiveness of our model in such a heterogeneous field. Finally, it is demonstrated that the MCR has the manipulability and potential to operate for RIRS by experiments in phantoms.

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The proposed model can predict the complicated nonlinear behavior of the MCR accurately in heterogeneous fields with external constraints. Here are several practical significances of the model: 1) It helps expand the effective workspace of the MNS. The coupled model can predict not only the deformation of the MCR in the central homogeneous region, but also the heterogeneous region beyond this region. 2) It can be used as a feedforward for practical control tasks, such as the tip trajectory control. However, it requires a trade-off between computing speed and precision. 3) It can predict deformation with external constraints. However, it requires the knowledge of the body-robot contacts, including position or load constraints along with the robot. This information can be captured by the localization systems, such as X-ray or ultrasound imaging system, and physiological sensors. Several problems need to be taken into account, such as real-time positioning and long operation time cannot be realized by the X-ray, and how the sensors are integrated on the miniature robot. Nevertheless, the model can be applied to virtual devices to train operators, which improves surgical efficiency and reduces X-ray irradiation time. Therefore, this model can help expand the practical application of MCR.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

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