AeCoM: An Aerial Continuum Manipulator with Precise Kinematic Modeling for Variable Loading and Tendon-slacking Prevention

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Abstract—Aerial robotic systems have raised emerging interests in recent years. In this article, we propose a novel aerial manipulator system that is significantly different from conventional aerial discrete manipulators: An Aerial Continuum Manipulator (AeCoM). The AeCoM compactly integrates a quadrotor with a tendon-driven continuum robotic manipulator. Due to the compact design and the payload bearing ability of tendon-driven continuum robotic arms, the proposed system solved the conflict between payload capacity and dexterity lying in conventional aerial manipulators. Two contributions are made in this paper: 1) a sensor-based kinematic model is developed for precise modeling in the presence of variable loading; and 2) a tendon slacking prevention system is developed in the presence of aggressive motions. The detailed design of the system is presented and extensive experimental validations have been performed to validate the system self-initialization, payload capacity, precise kinematic modeling with variable end-effector (EE) loadings during aerial grasping and tendon-slacking prevention. The experimental results demonstrate that the proposed novel aerial continuum manipulator system solves the constraints in conventional aerial manipulators and has more potential applications in clustered environments.

Index Terms—Aerial system, tendon-driven continuum robot, design and modeling, tendon-slacking.

I. SUPPLEMENTARY MATERIAL

Video: https://www.youtube.com/watch?v=5XUjcf_BjBc

II. INTRODUCTION

Unmanned aerial vehicles (UAVs) has attracted substantial interests among research and industrial communities for years. The functionalities are extended considerably when the UAVs are endowed with aerial manipulation skills for desired applications. Recently, aerial manipulation [1] has been an emerging research hotspot in the field of aerial robotics. An aerial manipulator (AM) generally combines a rotorcraft with specific robotic manipulator(s). The rotorcraft provides a robust aerial platform in air for stable hovering or movement, while the manipulation mechanism part conducts active operations. Many research studies have investigated different topics like physical interaction with environment [2], [7], aerial grasping [8]–[11], inspection and maintenance [12], [13], etc. In order to enhance robustness and stability, and broaden capabilities of the aerial manipulation systems, advanced techniques such as visual servoing control [14], motion planning and trajectory tracking control [15], or interaction contact force control [16] are explored.

A. Conventional Aerial Manipulators

In terms of system structure, several prototypes of aerial manipulators [1], [7] are designed and validated both in actual experiments. For UAV platforms, the unmanned helicopter and multi-rotor UAV are two dominant types. Unmanned helicopters have plenty of advantages in aerial manipulation: large payload capacity to carry one or several multi-DOF manipulator(s), advanced capability of long-flying duration and long-distance flight to fulfil time-consuming operation tasks [18]–[27]. Nevertheless, owing to complex mechanisms and complicated aerodynamic characteristics [28], which cause difficulties in controller design, unmanned helicopters are difficult to operate precisely.

Compared with helicopter platforms, multi-rotor UAVs (quadrotor, hexa-rotor, and octo-rotor) employed by a majority of research groups [29]–[39], are more popular in aerial manipulation, due to the mechanical simplicity, easy-to-deploy flight controller design, low vibration, low cost, and flying dexterity in indoors and outdoors. Furthermore, the manipulation mechanism has two main categories: a gripper and a robotic manipulator. A gripper is usually installed...
under the UAV fuselage, and located near the overall system center-of-mass (CoM), to conveniently conduct aerial grasping operations. Due to the light weight, no change of CoM, and no relative motion of grasped objects, grippers have little impacts on UAV dynamics [10], [40]–[46]. Robotic manipulators are more widely implemented and have many advantages over simple grippers. Manipulators’ multiple DOFs contribute to expanding workspace, enriching numerous functionalities, and enhancing mission adaptability. It should be noted that most of AM research is based on multi-DOF manipulators, and various categories have been emerging to fulfill specific requirements of aerial manipulation [2], [5], [25], [47]–[52], [52]–[56], as shown in Fig. 2.

Although aforementioned systems’ advanced advantages and potential in aerial manipulation are evident, some critical issues of current aerial manipulators (AM) are explored:

1) Aerial platforms such as helicopters or octo-rotor UAVs generally fly in open outdoor environments instead of unstructured and restricted space, owing to relatively large airframes and propellers. Also, these aerial manipulators are much heavier because of the weight brought by the manipulator part. These factors inevitably limits the workspace of AMs.

2) Lightweight UAVs can perform dexterous flights in most environments. On account of relatively low payload capacity, lightweight UAV platforms can only carry a gripper or a robotic manipulator with few DOFs. The platforms restrict the motion dexterity of the manipulators, and potential aerial applications are limited.

3) Particular manipulators shown in Fig. 2(c) are designed for special manipulation tasks, but lack flexibility and expansibility.

In summary, once DOFs of manipulators are intended to increase, more actuators are needed. It further increases the weight of conventional manipulators, and reduces the payload capacity of the systems. Then, much more powerful and larger aerial platforms are required, like helicopters as discussed. In other words, the conflicting relationship between the payload capacity and DOFs of current aerial manipulators restricts the improvement of aerial manipulation. Even though UAV platforms are well-developed, we still can explore some solutions on the focus of manipulator parts. Hence, in order to break the bottleneck, we concentrate on a novel type of the robotic manipulator: continuum robots. A continuum robot can be defined as a continuously bending, infinite-degree-of-freedom robot with an elastic structure [57]. A key advantage of continuum robots over conventional manipulators composed of several rigid links, is that, their weight is considerably lower for the same maximum output force. Moreover, continuum robots have increased flexibility, and thereby dexterity, thanks to the property of infinite DOFs [58].

The concept of the aerial continuum manipulator based on a simulation model, is theoretically proposed by Samadikhoshkho et al. [59]. For the first time, we originally design and manufacture an actual aerial continuum manipulator (AeCoM) which is composed of a lightweight quadrotor platform and a continuum robotic manipulator. Fig. 1 shows that the AeCoM is conducting aerial object grasping. The weight of the UAV platform is 750g, and its size is 320×320mm. The manipulator part whose weight is only 60g, is tendon-driven and has five segments. The key distinction between the proposed continuum part and previous tendon-driven continuum robots is that, we exploit lightweight, small-volume and powerful actuation motors, rather than extremely heavy and large DC motors or servo motors. Thus, the designed continuum manipulator which is carried by the UAV platform, can be floating in air instead of being fixed in stationary. It is noted that, the highly compacted mechanism design enables the UAV platform and the continuum manipulator into a unique integrated system.

B. Continuum Robot

Kinematics modeling plays an important role in the development of the proposed aerial manipulator. The accuracy of end-effector (EE) pose which is derived from the kinematics model, has direct impacts on the performance of aerial manipulation tasks. However, traditional constant-curvature kinematics widely used in continuum robots, fails to provide precise deformation of the manipulator under variable loadings, due to versatile EE devices such as grippers, sensors and other tools. It leads to complexity for the manipulator controller design and precise shape estimation. Data-driven techniques [60]–[62], sensor-feedback methods [63], [64], and mathematical models [65], [66] have been investigated to improve continuum robot kinematics under different loadings. To achieve better kinematics performance for the AeCoM, we incorporate an IMU sensor installed at the EE tip to assist in the kinematics modeling. Results show that the error of EE position estimation is less than 3mm within the range of loading: 0 – 500g.

Generally, continuum robots critically suffer tendon slackness and low velocity during bending motions, even for the
AeCoM. Such tendon loosing harmfully affects the controller accuracy and motion continuity. Typically for AeCoM, during aggressive maneuvers or challenging aerial manipulation tasks, the risk of tendon slacking rises dramatically. To address the issue of tendon slacking, researchers have investigated many approaches, which are categorized as three aspects: mechanical design, sensor assistance and numerical models. Nevertheless, mechanism structures bring extra weights and increase the system complexity. Even though the tendon tension could be maintained to prevent tendon slacking, most of the sensors are additionally installed and introduce unexpected weights. Based on the numerical models which provide shape estimation of the continuum robots, controller outputs can be adapted to ensure tension maintenance. However, the models are typical, owing to relying on parameters of the materials. With the prevention of tendon slacking, we design a cascade sensor-feedback controller for the AeCoM to implement realtime attitude control, even in fast motions. Experiments validate that the attitude tracking of EE has extremely low error during consecutive aerial motions, without tendon slacking.

C. Contributions

To prove the feasibility of the AeCoM, several experiments are conducted. The results show validation of the system self-initialization, payload capacity, manipulator control for tendon-slacking prevention, accuracy of the proposed kinematics model, and accuracy of EE tracking motion in spatial space. Aerial object grasping is also conducted to verify the overall performance of the proposed system. The main contributions of this article can be summarized as follows:

1) To the best of authors’ knowledge, we propose a novel aerial manipulation system for the first time: aerial continuum manipulator (AeCoM), with original mechanical design. The system has advantages of motion dexterity and payload capacity over conventional aerial manipulators.

2) An IMU-sensor based kinematics modeling methods is proposed to obtain precise EE poses under variable loadings. Experiments of aerial bending motion and object grasping are conducted to prove the distinct accuracy.

3) By employing the IMU and torque sensors, a cascade attitude-rate-tension manipulator control method is derived to implement accurate attitude control and prevent tendon slacking during aggressive bending motions.

III. DESIGN

In this section, an overview of the system architecture including the hardware design and the mechanism structure, is illustrated in detail, and the comparison with conventional aerial manipulators is also presented.

A. Hardware Design

The hardware architecture is divided into three independent subsystems: an automatic decision system, a UAV platform and continuum robotic system. The hierarchical hardware design establishes the solid basis of the AeCoM. The decision system is based on a high-performance onboard PC, which is responsible for receiving and processing sensing information, and generating unified motion commands. The UAV platform is a quadrotor with the size of $320 \times 320 \mathrm{mm}$. The last one involves a micro-controller board as the core, torque sensors, IMUs, and several functional servo motors. The latter two subsystems directly connect to the onboard PC via serial ports, which form stable communication channels. Key hardware components with detailed models are listed in Table. Also, the system workflow including signals communication between the three subsystems and key onboard tasks, is shown in Fig.

| Hardware components | Quantity | Model       |
|---------------------|----------|-------------|
| Onboard PC          | 1        | Dji manifold-v2 |
| Flight controller   | 1        | PixRacer-micro |
| Propeller motors    | 4        | T-motor F90  |
| Micro cortex-3 arm board | 1     | Stm32F1VCT6   |
| Tendon motors       | 4        | FeeTech-STS3032 |
| USB-TTL communication board | 1    | FeeTech-URT1   |
| IMU sensor          | 1        | MPU9250      |
| Digital servo motors for landing | 2 | RDS3115       |
| Servo motor of the gripper | 1 | FeeTech-HWZ2020 |

| Mechanism (material) | Quantity | Weight (each) |
|----------------------|----------|---------------|
| Base disk (PLA)      | 1        | 5g            |
| Intermediate disk (PLA) | 4   | 3g            |
| End disk (PLA)       | 1        | 4g            |
| Joint shaft (PLA)    | 5        | 2g            |
| Pin shaft (Metal)    | 10       | 1g            |
| Supporting spring (Metal) | 20  | 0.5g          |
| Tendon motor (Hybrid) | 4     | 20g           |
| Landing rod (Carbon) | 2        | 4g            |
| Rotor frame (Plastics) | 1   | 30g           |

B. Mechanical Design

To incorporate a continuum robotic system into an aerial platform, the entire weight, payload capacity and control accuracy or dexterity should be considered. In order to reduce the weight as much as possible, soft material is first taken into account. Despite of the property of light weight, soft material has the deadly drawback that its stiffness is not sufficient enough, such that the whole soft manipulator can not carry large loadings. Under this situation, its payload capacity is severely limited, and also the soft material is mostly driven by pneumatic pumps, which are too heavy for the aerial system. Therefore, instead of pneumatic driving, we deploy a tendon-driven system, which is actuated by several motors. Moreover, we use the 3D-printing material (lightweight) to produce main mechanical components of the continuum robotic arm.

To achieve larger workspace, the prototype consists of five consecutive segments to extend its bending range, as shown in Fig. Each segment is composed of two cross disks, which are connected by a mechanical gimbal, and four springs evenly distributed in each disk as supporting structures. The bending motion is actuated by four tendons which are driven by four motors with torque feedback. Of note, the key factor
of production of the manipulator, is the usage of the specific motor whose weight is only 20g. In addition, each motor could provide the maximum torque of $3.5N \cdot m$, and its volume is 0.15$cm^3$. In other words, due to extinct mechanical properties, the motors facilitate optimization of the system structural layout where the actuation part of the robotic arm is compacted into a highly limited space, and also supply with necessary actuation for satisfying different complicated motion.

Regarding the space distribution of four actuation motors or tendons, one pair of diagonal tendons manipulates the robotic arm’s bending motion within the plane of the tendons, while the other diagonal tendons control the perpendicular bending motion. From the perspective of mechanical design, the gimbal only restricts two DOFs of rotational motion, such that there is no twist moment occurred during the manipulator’s motion. Therefore, the bending motions triggered by the two pairs of diagonal tendons which are strong fish cables, are totally independent. Considering accurate end-effector (EE) pose estimation, we employ an IMU sensor which is installed centrally on the EE tip, to obtain real-time and precise attitude...
information, as shown in Fig. 5. The roll axis is corresponding to one of the two pairs, and the pitch axis aligns to the other tendon pair. The bending motions of the tendon pairs can be detected by IMU’s attitude changes. Discussing the structural layout, every component is evenly distributed around the center of mass of the whole system, which leads to the best weight balance.

Compared with previous continuum robots with similar structures, the proposed design uses optimized cross-sectional disks instead of solid circular disks. The aim is to reduce unnecessary weight of the disks, and maintain enough structural strengths. Table II presents information of each detailed mechanical element, including quantity, weight and material. For most of feasible aerial manipulation systems, one structural part which can not be overlooked is the auxiliary landing rods. The landing rods are used to support the whole aerial system, before or after conducting aerial flights, to prevent unnecessary physical damages on the manipulator. However, static landing rods will definitely shrink the workspace of the robotic arm. Therefore, we design a pair of landing rods which can change their placement by controlling corresponding servo motors, as shown in Fig. 4. When the AeCoM is on the ground, the landing rods switch to the standing mode to sustain the manipulator. When the AeCoM is conducting aerial flights, the landing rods rotate by 180° and point to the above direction, such that the manipulator’s motions are not affected.

### C. Comparisons

In the perspective of mechanism, the AeCoM has advantages over conventional aerial manipulators, and also most of continuum robots. To compare with aerial manipulators, the weight and DOFs of the manipulator are predominant. The payload capacity is defined as the ratio between the maximum loading weight and the weight of whole aerial system, while the number of DOFs decides system dexterity. To compare with current continuum robots, the payload capacity which decides the maximum limit of loading, is the key factor. Also, the simplification of controlling box including the reduction of volume and weight, should be taken into account. Since the UAVs are aerial mobile platforms, the controlling box of the continuum manipulator can not be too large and heavy. Fig. 6 presents the detailed comparison result of mechanical properties. In Fig. 6(a), the UAV weight, the robotic arm weight and DOFs of the arm taken as three caring factors, the comparison result between the AeCoM and well-noted aerial manipulators are listed in a histogram chart. It is evident that, the AeCoM has the lowest weight of the UV platform and the robotic arm part, while its DOFs achieve 5 that is the highest among the list. Fig. 6(b) compares the payload capacity of the AeCoM and current continuum robots. It shows that the AeCoM has a floating base which has much better mobility, and its payload capacity is the highest (600g).

### IV. Modeling

This section presents the forward and inverse kinematics model, and the dynamic model of the AeCoM. To describe the configuration of the system, we introduce the inertial frame $W$, the UAV body frame $V$, the base frame of the manipulator $B$, and the end-effector frame $E$, as shown in Fig. 7. We define the generalized coordinates for the system, including UAV position $p = [x, y, z]^T$ and attitude $\eta = [\psi, \theta, \phi]^T$ with respect to the inertial frame. As for the continuum manipulator part, we define $\lambda = [L, \alpha, \beta]^T$ to represent the configuration space of PCC model in the base frame, and the tendon actuation space $q = [q_1, q_2, q_3, q_4]^T$ denoting the changes of the tendon lengths.

#### A. System Kinematics Model

The system kinematics model is established to describe spatial motion relationships between key frames $(W, V, B, E)$. With the model, it is convenient to compute all the frames’ poses with respect to the inertial frame. However, what we most concern is to obtain the accurate pose of the end-effector, which is crucial to versatile manipulation tasks. To achieve this, we build a fundamental kinematics chain for the system as:

$$W^P_{ee} = T_V^W \cdot T_B^V \cdot T_E^B \cdot P_{ee}$$

(a) A histogram of arm weight and DOFs of arm for comparing the AeCoM and current aerial manipulators. (a)-[1 - 11] are published aerial manipulators in the survey \[1\], \[17\]. (b) A histogram of the base property and payload limit for comparing the AeCoM and current continuum robots. (b)-[1 - 11] are published continuum robots in the survey \[57\], \[58\], \[60\].
curvature and stiffness of the continuum body are affected by the tendon-slacking issue, but variable loadings still affect the configuration space, the fast manipulator maneuver is a challenge for the AeCoM in aerial manipulation. The result of fast maneuvers conducted by the tendon-driven continuum robot is that, the tendon slacking occurs frequently. The tendon slacking leads to enormous errors of the actuation space. In this article, the controller of the AeCoM in Sec. V address the tendon-slacking issue, but variable loadings still affect the actuation space.

C. Precise Kinematic Modeling With Variable Loading

Although the geometric relation directly gives a solution for the configuration space from the actuation space, the result is only effective when there is no loading on the end-effector. The curvature and stiffness of the continuum body are affected by external loading. Thus, given the same configuration space, the conventional continuum kinematics model\[81\] under variable loadings, the EE’s pose is doomed to be not accurate.

\[q_i = n \cdot L_s - L_i, \quad i = 1, 2, 3, 4\]
\[L_i = L - \alpha \cdot r \cdot \cos[\beta + (i - 1)\mu]\]
\[L \approx \frac{L_s \cdot \alpha_s}{2\sin(\alpha_s/2)}, \quad \alpha_s = \alpha/n\]  

where \(n\) shows the number of segments of the continuum body, \(L_s\) denotes the constant length of a single segment, \(L\) denotes the approximated circular length, \(\alpha\) represents the bending plane angle, and \(\beta\) is the twist plane angle. It is convenient to produce the task space through the configuration space, as shown in Fig. 8.

As depicted in Fig. 7, the continuum robotic arm is regarded as a bending circular beam with four actuation tendons, which are distributed in the interval of \(\mu = \frac{\pi}{2}\). Due to the mechanical design, we assume that the whole continuum body is approximately curvature-constant. It means that every point on the continuum body is supposed to have the same constant curvature during the bending motion. Based on the assumption, the geometric relationship between bending motion and tendon lengths is built to determine the resulting shape of the continuum part. Given an arbitrary continuum shape shown in the Fig. 7 the actuation space \(q\) is generated by tendon motors’ encoders. The relationship between the actuation space \(q\) and the continuum configuration space \(\lambda\) is built as:

\[
\begin{pmatrix}
  q_1 \\
  q_2 \\
  q_3 \\
  q_4
\end{pmatrix} = \begin{pmatrix}
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  n \cdot L_s - L_2 \\
  n \cdot L_s - L_3 \\
  n \cdot L_s - L_4
\end{pmatrix}
\]

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\]

\[
\begin{pmatrix}
  q_1 \\
  q_2 \\
  q_3 \\
  q_4
\end{pmatrix} = \begin{pmatrix}
  1 & 0 & 0 & 0 \\
  0 & 1 & 0 & 0 \\
  0 & 0 & 1 & -d_s^i \\
  0 & 0 & 0 & 1
\end{pmatrix}
\]

where \(n\) shows the number of segments of the continuum body, \(L_s\) denotes the constant length of a single segment, \(L\) denotes the approximated circular length, \(\alpha\) represents the bending plane angle, and \(\beta\) is the twist plane angle. It is convenient to produce the task space through the configuration space, as shown in Fig. 8.

As we have discussed the conventional kinematics model based on the geometric relation between the actuation space and the configuration space, the fast manipulator maneuver is a challenge for the AeCoM in aerial manipulation. The result of fast maneuvers conducted by the tendon-driven continuum robot is that, the tendon slacking occurs frequently. The tendon slacking leads to enormous errors of the actuation space. In this article, the controller of the AeCoM in Sec. V address the tendon-slacking issue, but variable loadings still affect the actuation space.

B. Kinematics Affected By Fast Manipulator Maneuvers

As depicted in Fig. 7, the continuum robotic arm is regarded as a bending circular beam with four actuation tendons, which are distributed in the interval of \(\mu = \frac{\pi}{2}\). Due to the mechanical design, we assume that the whole continuum body is approximately curvature-constant. It means that every point on the continuum body is supposed to have the same constant curvature during the bending motion. Based on the assumption, the geometric relationship between bending motion and tendon lengths is built to determine the resulting shape of the continuum part. Given an arbitrary continuum shape shown in the Fig. 7 the actuation space \(q\) is generated by tendon motors’ encoders. The relationship between the actuation space \(q\) and the continuum configuration space \(\lambda\) is built as:

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  0 & 1 & 0 & 0 \\
  0 & 0 & 1 & -d_s^i \\
  0 & 0 & 0 & 1
\end{pmatrix}
\]

where \(n\) shows the number of segments of the continuum body, \(L_s\) denotes the constant length of a single segment, \(L\) denotes the approximated circular length, \(\alpha\) represents the bending plane angle, and \(\beta\) is the twist plane angle. It is convenient to produce the task space through the configuration space, as shown in Fig. 8.

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C. Precise Kinematic Modeling With Variable Loading

Although the geometric relation directly gives a solution for the configuration space from the actuation space, the result is only effective when there is no loading on the end-effector. The curvature and stiffness of the continuum body are affected by external loading. Thus, given the same configuration space,
the corresponding actuation space is different under variable loading. As a result, the relation \[ \mathbf{R} \] can not compute the accurate continuum configuration only by employing tendon lengths, under this situation. We introduce an IMU sensor installed on the end-effector plane, as shown in Fig. 7 to assist in solving more precise configuration. The sensor is modeled as [82]:

\[
\mathbf{R} = R^T(\mathbf{R}_e - \mathbf{g}) + \mathbf{b} + \mathbf{a}
\]

where \( \omega_m \) is the measured angular velocity and \( \omega_e \) is the true angular velocity. Also, \( \alpha_m \) and \( \alpha_e \) represent the measured acceleration and true acceleration, respectively. \( \mathbf{b}_g \) and \( \mathbf{b}_a \) are the random measurement bias. \( \mathbf{b}_g \) and \( \mathbf{b}_a \) are zero-mean gaussian white noise.

Thanks to mechanical restraints of the continuum robotic arm, there is only bending motion rotating around the pitch and roll direction, without any twisting motion rotating around the yaw direction. It is noted that the IMU on the end-effector and the IMU on the UA body share the same pitch and roll direction, as depicted in Fig. 7. Thus, we employ the attitude information of the two IMUs to compute the spatial relation between the base plane and the end-effector plane. Furthermore, the continuum configuration can be obtained by the spatial relation. To define two planes numerically, we denote the attitude of the EE plane as \( \theta_{ee} \) and \( \phi_{ee} \), the attitude of the base plane as \( \theta_b \) and \( \phi_b \). The orthogonal basis vectors of the EE plane \( [\mathbf{v}_{ee,r} \mathbf{v}_{ee,p}]^T \) and the base plane \( [\mathbf{v}_{b,r} \mathbf{v}_{b,p}]^T \) are defined as:

\[
\mathbf{v}_{ee,r} = \begin{bmatrix} \cos \theta_{ee} \\ 0 \\ \sin \theta_{ee} \end{bmatrix}, \quad \mathbf{v}_{ee,p} = \begin{bmatrix} \cos \theta_b \\ 0 \\ \sin \theta_b \end{bmatrix}
\]

\[
\mathbf{v}_{ee,p} = \begin{bmatrix} 0 \\ \cos \phi_{ee} \\ \sin \phi_{ee} \end{bmatrix}, \quad \mathbf{v}_{ee,p} = \begin{bmatrix} 0 \\ \cos \phi_b \\ \sin \phi_b \end{bmatrix}
\]

The normal vectors of the two planes are computed as:

\[
\mathbf{n}_{ee} = \mathbf{v}_{ee,r} \times \mathbf{v}_{ee,p} \\
\mathbf{n}_b = \mathbf{v}_{b,r} \times \mathbf{v}_{b,p}
\]

Then, the included angle \( \epsilon_n \) of the two planes, which is regarded as the bending angle \( \alpha \). Based on IMU sensors, the continuum configuration is given as:

\[
\alpha = \epsilon_n = \mathbf{n}_{ee} \cdot \mathbf{n}_b, \quad \epsilon_n \leq \frac{\pi}{2}
\]

\[
\beta = \mathbf{b} \cdot \mathbf{n}_{ee} \cdot \mathbf{v}_+ >
\]

where the symbol denotes the included angle of two vectors, \( \mathbf{n}_{ee} \) denotes the projection vector of the \( \mathbf{n}_{ee} \) in the base plane, and \( \mathbf{b} \cdot \mathbf{v}_+ \) is defined as the benchmark direction of the base plane. The twisting angle \( \beta \) is derived by the included angle between the projection vector and the benchmark vector.

With the configuration of the continuum part, we can derive the translation of the EE with respect to the base frame, as:

\[
\begin{bmatrix} x_{ee} \\ y_{ee} \\ z_{ee} \end{bmatrix} = \frac{L}{\alpha} \begin{bmatrix} (1 - \cos \alpha) \cos \beta \\ (1 - \cos \alpha) \sin \beta \\ \sin \alpha \end{bmatrix}
\]

where \( L \) denotes the approximated circular length, as presented in equ. (3). Inversely, to compute desired continuum configuration with the targeted translation, we have:

\[
\begin{bmatrix} \alpha \\ \beta \end{bmatrix} = \begin{bmatrix} 2 \arccos\left(\frac{|x_{ee}|}{||P_{ee}||}\right) \\ \arctan\left(\frac{y_{ee}}{z_{ee}}\right) \end{bmatrix}
\]

With the compensation of the IMU on EE, we obtain more precise continuum configuration for realtime kinematic solving, which will be validated under different loading in the experiment section.

V. CONTROL

This section presents the control framework of the AeCoM system. To achieve this, we employ the centralized control strategy and divide the whole system into two control subsystems: the aerial platform controller and the continuum manipulator controller. Although the two controllers are independent, they share the comprehensive state of the integrated system and are derived from the same dynamics model. The most fundamental application for the AeCoM is to actuate the end-effector under the proposed controller, to precisely approach to a desired pose in the inertial frame. Considering the manipulator part is a tendon-driven robotic arm, the controller should be capable of preventing tendon slacking during consecutive motion.

A. UAV Controller With A Continuum Manipulator

Given a desired object pose for the end-effector of the AeCoM, we design a controller for the UAV platform to track the associated pose that is derived by the system inverse kinematics. Here, the UAV state is denoted by \( \mathbf{X} = \{ \mathbf{p}, \mathbf{R}, \mathbf{p}, \Omega \} \), including the UAV position \( \mathbf{p} \in \mathbb{R}^3 \), its rotation \( \mathbf{R} \in SO(3) \), the linear velocity \( \mathbf{p} \in \mathbb{R}^3 \), and the angular velocity \( \Omega \in \mathbb{R}^3 \). By this notation, and denoting the columns of \( \mathbf{R} \) as \( \mathbf{R} = [r_x \ r_y \ r_z] \), the UAV dynamics model [83] can be derived by:

\[
\begin{align*}
\dot{\mathbf{p}} &= \mathbf{g} + f \mathbf{b} \\
\dot{\mathbf{R}} &= \mathbf{R} \Omega \\
\dot{\mathbf{J}_f} &= -\mathbf{J} \Omega + \mathbf{J} \mathbf{r} + \mathbf{f} \tau + \mathbf{f}_\text{arm}
\end{align*}
\]

where \( m \) is the total mass of the AeCoM, \( g \) is the gravity vector, \( J \) is the moment of inertia, \( f \) is the scalar thrust force (applied at the quadractor center of mass and along the local vertical direction \( \mathbf{b}_z \) resulting from the propeller forces \( f_1, f_2, f_3, f_4 \) \( \mathbf{r} \in \mathbb{R}^3 \) is derived by the propeller forces, and \( \mathbf{f}_\text{arm} \) is the torque exerted by the continuum robotic arm. In eq. (10), the symbol \( \times \) is the vector cross product, the hat map \( \hat{\cdot} \) maps a 3D vector to a \( 3 \times 3 \) skew-symmetric matrix, and its inverse operation, the vee map \( \vee \) maps a \( 3 \times 3 \) skew-symmetric matrix to a 3D vector.

The UAV controller takes input a desired state \( \mathbf{X}^* = \{ \mathbf{p}_d, \mathbf{R}_d, \mathbf{p}_d, \Omega_d \} \) and computes the convergence errors:

\[
\begin{align*}
\mathbf{e}_p &= \mathbf{p}_d - \mathbf{p} \\
\mathbf{e}_\mathbf{R} &= \mathbf{R}_d - \hat{\mathbf{R}} \\
\mathbf{e}_\Omega &= \hat{\mathbf{R}}^T \mathbf{R}_d \Omega_d - \mathbf{\Omega}
\end{align*}
\]

where e denotes the position error, \( \mathbf{R}_d \) is the desired orientation, and \( \Omega_d \) is the desired angular velocity.
Then, the conventional continuum control law is given as:

$$\tau_{con} = -k_p e_L - k_i \int e_L + f_\mu$$

where $\tau_{con}$ is the output torque vector, $k_p$ and $k_i$ are control gains, and $f_\mu$ is the friction force on tendons. The main drawback is that the conventional control law drives all the motors separately. It turns out, the motion velocity of the continuum robots is restricted heavily, because independent torques on different tendons produce unaligned “pull” and “push” velocity. If the “pull” velocity is much higher than the other one, the robots could be damaged. Inversely, a higher “push” velocity easily leads to tendon slacking. Therefore, the conventional continuum robots commonly move in slow velocity.

To improve the motion velocity for the AeCoM during aerial tasks, we introduce the IMU as discussed in the kinematics Sec. [V] to design a new control law. Considering the mechanical structure of the manipulator, two diagonal pairs of tendons are aligned with the pitch and roll axis correspondingly. Thus, the push-pull movement of one pair of tendons decides the associated attitude changes. Meanwhile, the attitude of the EE plane is deeply binding with the manipulator’s configuration space, as presented in section [IV] The rotation state of the IMU on the EE is defined as $E = \{\theta_c, \phi_c, \omega_\theta, \omega_\phi\}$ including the rotation $\{\theta_c, \phi_c\}$, and the angular velocity $\{\omega_\theta, \omega_\phi\}$. Then, the cascade attitude-rate-tension cascaded controller (AttiFB) is built as:

$$e_\theta = \begin{bmatrix} \dot{\theta}_{c,d} - \theta_c \\ \dot{\phi}_{c,d} - \phi_c \end{bmatrix}, \quad \dot{e}_E = \begin{bmatrix} \dot{\theta}_{c,d} - \theta_\theta \\ \dot{\phi}_{c,d} - \phi_\phi \end{bmatrix},$$

$$\tau_{AttiFB} = -k_{c,p} e_\theta - (k_{c,p} \dot{e}_E + k_{c,i} \int \dot{e}_E) + f_\mu$$

where $\tau_{AttiFB}$ is the output torques on the pairs of tendons associated with motion velocity. The AttiFB controller establishes the relation between the torques and motion velocity. However, if the AeCoM is conducting consecutive manipulation operations, repeatable and wide bending motion of the robotic arm could cause tendon slacking without considering the lose of tendons’ tension.

### B. Manipulator Control For Aggressive Maneuvers

Since the necessity of dealing with variable loading for the AeCoM is discussed, we are only left to design a continuum manipulator controller to implement agile bending motion and prevent tendon-slacking. We start from conventional control methods for tendon-driven continuum robots. These methods generally establish a sole geometric relation between the actuation space (tendon lengths actually) and the configuration space. It is noted that, current tendon lengths can be derived by the mechanism design and actuation motors’ properties (mostly encoders) in real time. Given a desired continuum shape, the desired configuration space, the desired tendon lengths are computed. The length error vector is built as:

$$e_L = L_d - L$$

$$L = [L_1, L_2, \ldots, L_n]^T$$

and

$$f = -b^T(k_p e_p + k_v e_v + m b - m \ddot{p}_d)$$

$$\tau = -k_R e_R - k_\Omega e_\Omega \Omega \times J \Omega$$

$$- J(R^T R_d \Omega_d - R^T R_d \Omega_d)$$

where $k_p$, $k_v$, $k_R$, $k_\Omega$ are tuned control gains. The controller enables the AeCoM to implement accurate positioning and trajectory tracking motion, which will be validated in the Sec. [VI]. In other words, the UAV controller dominates widely but roughly translational movements of the AeCoM, while precise trajectory tracking motion, which will be validated in the Sec.

### C. Tendon-slacking Prevention Controller Design

The term “tension” describes the pulling force transmitted axially along tendons. Thanks to the torque sensors embedded inside the tendon motors, the force applied on tendons is obtained by corresponding sensors. Thus, based on the AttiFB controller, we propose an attitude-rate-tension cascaded controller for the continuum manipulator. Given a set-pose of the end-effector, the translation part could be transformed to configuration parameters (the bending angle and twisting angle), which are transformed to attitude. In other words, the control of EE attitude equals to the control of EE’s pose. Here we introduce the bending moment $m = [m_\theta, m_\phi]^T$ for the continuum manipulator to describe the extent of bending motions, which are caused by the discrepancy of tensions. With the torque sensors, we define a tension vector $T = [t_1, t_2, t_3, t_4]^T$ for tensions applied on four tendons. The
relationship between the bending moment \( m \) and the tension vector \( T_i \) is established as:

\[
m = \begin{bmatrix} \hat{m}_\theta \\ \hat{m}_\phi \end{bmatrix} = \frac{m_{sp}}{||m_{sp}||} \begin{bmatrix} t_1 - t_3 \\ t_2 - t_4 \end{bmatrix}
\]

Then, the bending moment control layer is given as:

\[
e_m = m_{sp} - m
\]

\[
\tau_{sp} = k_{m,p} \cdot e_m + k_{m,i} \cdot \int e_m \cdot dt + k_{m,d} \cdot \dot{e}_m
\]

where the resulting torques \( \tau_{sp} \) have the constraint of both motion velocity and tendons’ tension.

The proposed manipulator controller has three cascaded control layers, which aims to take attitude, rate and tension into account. The innermost layer introduces tension constraints for controlling each motor, to restrict lowest tension for each tendon, which leads to prevention of tension loss and resulting tendon slacking. The validation and comparison results will be demonstrated in the Sec. VI.

VI. EXPERIMENTS AND RESULTS

This section presents comprehensive evaluation of the proposed aerial system including five interconnected aspects. The arrangement of the experiments is set as system initialization for keeping tendons pre-tension, payload capacity validation during flights, robotic arm controller for IMU-feedback bending motion and tendon-slacking prevention, validation of the kinematics model for computing accurate EE poses with respect to the UAV frame, and aerial grasping for actual objects.

A. Automatic System Initialization

For any tendon-driven continuum robots, it is necessary to initialize the continuum body displacement and tendon tension. If tendons are not tensioned or are slacken, the following motion absolutely has unpredictable errors. Therefore, keeping tendons’ tension within a limited range is indispensable. Normally, the tendons are tightened manually or by mechanism for pre-tensioning, before any motions. However, these external interventions are tedious and not user-friendly, especially in repeatable applications. For instance, most studies commonly use manual ways, which involve plenty of system burden and waste of time. On the other hand, the mechanism brings extra weights, which are supposed to be removed for an aerial system. These traditional initialization approaches are useful but time-consuming. For the proposed system, an aerial continuum manipulator, we intend to simplify the initialization process with least resources.

We utilize the torque sensors and the IMU to implement an automatic self-initialization method, which could ensure that the continuum robotic arm adjusts to the perfect attitude (the EE plane parallel to horizontal plane) quickly and each tendon is tensioned equally, without any manual or mechanical assistance. To achieve this, two conditions have to be fulfilled. One is to maintain the EE’s attitude within a limit (pitch and roll angles from the IMU less than 1°). Another one is to keep all the tendons’ tension exceed a predefined value. Essentially, the change of the EE’s attitude and tendons’ tension is through controlling the tendons’ actuation motors, according to feedback of the tension and IMU sensors. To validate the feasibility and efficiency of the proposed initialization method, we randomly test the method 20 times and record every duration from the system powering on to completion of the initialization.

Fig. 11 presents the duration of each initialization process. 20 times initialization tests are carried with records of the duration.

![Fig. 10. The digital process of the system initialization. (a) Disturbance stage: external intervention is put on the robotic arm. (b) Initialization process is conducted.](image)

![Fig. 11. The repeatability evaluation of the system initialization. 20 times initialization tests are carried with records of the duration.](image)
we set a group of several loadings including holds the loading during any manipulation motion. Therefore, maximum loading during any flights, while the robotic arm and the robotic arm. It means that the UA V carries the maximum limit of loadings. It should be noted that, the objects. To ensure that the aerial system has the capability of different devices on the end-effector or various interaction tasks, it is inevitable to deal with variable loadings, such as aerial manipulation system. For versatile aerial manipulation B. Payload Capacity Validation

The experiment proves that, the initialization method enables the whole system self-initialization automatically, compared with the previous pre-tensioned approaches, even suffering from aggressive disturbance. The initialization method is useful and fundamental for the continuum robotic arm, and also saves time and weight for the AeCoM.

B. Payload Capacity Validation

Payload capacity is an important factor for evaluating an aerial manipulation system. For versatile aerial manipulation tasks, it is inevitable to deal with variable loadings, such as different devices on the end-effector or various interaction objects. To ensure that the aerial system has the capability of carrying these loadings, the payload capacity test is needed. To evaluate the payload capacity, the key is to decide the maximum limit of loadings. It should be noted that, the maximum payload could be carried by both the UAV platform and the robotic arm. It means that the UAV carries the maximum loading during any flights, while the robotic arm holds the loading during any manipulation motion. Therefore, we set a group of several loadings including 0g, 50g, . . . , 500g with the interval of 50g, and equip the system with these loadings. Then, the AeCoM flies to a certain height and hover, and a single-axis bending motion (pitch: 0° to 90°) of the robotic arm is conducted to test the lifting.

Fig. 12 shows the test result with a 500g loading. The desired bending angle is set as 90° and the controller could change the shape of the robotic arm to make the current angle achieve the expected angle. It proves that the aerial system could lift at least weight of 500g during aerial manipulation. Two evaluation criteria should be taken into account. One is the rising time, which is defined as the duration of the bending motion from 0° to 90°. The other one is the convergence error between the attitude of the IMU and the expected attitude. Both criteria are shown in Fig. 12. According to the loading group, 10 sets (0g, 50g, . . . , 500g) are tested in hovering flights with same robotic arm motion. Then, Table II presents steady-state error and rise period during the designed bending motion under variable loading (0g−500g). It reveals that the difference of loading lifting performance among the group is little.

C. Tendon-slacking Prevention Controller Evaluation

Since the payload test has proved the payload capacity of the AeCoM, it is not doubted that the system is able to carry loading less than 500g. Then, the controller of the robotic arm is required to validate for random motion within 500g loadings. To cope with complex aerial application tasks, the proposed system is required to have delicate motion response. Thus, fast bending motion for the manipulator is needed to address, even thought it brings high possibility of tendon slacking. As we discussed in section V, due to attitude and tension feedback, experiments of aerial fast motion are designed to validate the capability of slacking avoidance. During hovering flights, the AeCoM conducts consecutive swing motions in a large margin, following the pitch and roll axes respectively. The loading is set as 260g, which is the weight of the gripper. To prove that there is no slacking occurred during the aggressive motions, the difference between the current attitude and desired attitude should be limited strictly. On the other hand, if the current attitude can not chase the desired attitude, it is evident that the tendons can not provide enough actuation to manipulator the continuum body. Under this situation, the tendon slacking happens.

Fig. 14 presents the change of EE’s attitude with desired attitude, during the designed consecutive motions. The real-time discrepancy between the desired attitude and the current attitude is depicted in the figure. It can be seen that, the error fluctuates around 0° during the 90s motion, with the 260g loading. The maximum angular velocity is 0.52 rad/s. It means that the motion is conducted successfully without any tendon slacking. Also, different loadings for the same motion are validated, with average error shown in Table III. To further prove the feasibility and performance of the proposed manipulator controller, we tested continuous swing motion using the designed controller, attitude-feedback controller and the
conventional continuum controller. The experimental motion is defined as single axis swing motion in large extent. When the aerial manipulator is hovering, the robotic arm conducts swing motion along the roll axis, according to a list of desired attitudes. The attitude control performance result is shown as Fig. 13.

The experiment compares the three controllers under the predefined motion. According to the comparison between the proposed controller and the attitude-feedback controller, they have the same performance on attitude tracking at the first several periods, such as similar response rate and fitting curves. However, without tension feedback, the attitude-feedback controller lost the capability of tracking due to tendon losing. The proposed controller could maintain stable and robust tracking performance. Another comparison between the proposed controller and the conventional continuum controller shows that, the latter one can not handle fast tracking response.

D. Precise Kinematics Modeling Validation

As we discussed the kinematics model for obtaining accurate poses of the end-effector, it is challenging to validate the accuracy of the designed kinematics model. The translational part is the key factor, which decides the relative position of the end-effector with regard to the UAV platform. Here we utilize the vicon system to obtain both poses of the UAV and the end-effector, and the discrepancy is regarded as the translational measurement in groundtruth. The aerial system is commanded to conduct hovering flight and bending motion of the robotic arm. To comprehensively evaluate the model, the range of the bending motion should be as large as possible. Thus, we design single-axis bending motion with roll (−90° to 90°) and pitch (−90° to 90°), and dual-axis combination motion which makes the end-effector draw circles. During the whole bending motion, the proposed kinematics model and conventional model produce translational solution in \( X−Y−Z \). Then, we compare the results of the two models with the vicon groundtruth under the loading of \( 300g \), as shown in Fig. 15.

To demonstrate the accuracy of the proposed kinematics model under different loading, we set a group of different weight added on the end-effector. Then we compute the root mean square error (RMSE) to present the accuracy of the proposed model and the conventional model. Under these loading, the RMSE of both models with regard to weight...
Fig. 15. The proposed kinematics model evaluation with comparison with the conventional kinematics model, under the 300g loading. The X−Y−Z coordinates denote the local translation of the EE relative to the AeCoM base frame.

Fig. 16. The root mean square error (RMSE) of the proposed kinematics model under variable loadings, with result of the conventional model.

is depicted in Fig. 16. The RMSE results show that, with increase of the weight, the RMSE of the proposed model is limited within 30mm, while the RMSE of the conventional model reaches around 350mm under 300g. The result proves that, the proposed model could provide stable and satisfactory translational accuracy for the end-effector during consecutive bending motions.

With the kinematics model, it is possible to compute the real-time pose of the end-effector in the world coordinate with known global UAV poses. For aerial manipulation tasks, the pose of the end-effector is vital for actual interaction with the surroundings. We design a flight maneuver which makes the AeCoM track the desired path to evaluate the end-effector positioning and tracking performance. During the tracking flight, the UAV and the manipulator conduct movements simultaneously. We record the desired path and AeCoM’s paths in Fig. 17 where realtime translational data of the EE is presented. It can be seen that, the height control has quite high accuracy but horizontal translation control has some delays. The average RMSE is 0.202m.

E. Aerial Grasping

To validate the comprehensive functionality of the AeCoM, we design aerial grasping experiments. The aerial grasping is a challenge for payload capacity, accuracy of the kinematics model and the AeCoM controller. A bottle is chosen as the target object, because it is easy to change its orientation. The designed experimental process includes the grasping stage, the placing stage and the return stage. During the grasping stage, the AeCoM flies from a distant point to the object point. Meanwhile, the manipulator changes its orientation gradually to align with the object’s orientation. When the gripper reaches the object, the gripper’s pose should be equal to the object’s pose. After the grasping stage, the AeCoM takes the object to a predefined position where a basket is put, and drops the object. Then, the AeCoM returns to the original starting point. The whole process is conducted automatically.

Fig. 18 presents the aerial grasping stage with complete maneuver details. The object is placed in three lean angles: 15°, 50°, 80°. The successful rates for different object angles are presented in Fig. 20. With the increase of the angle, the grasping becomes more difficult. Fig. 19 records realtime translation and orientation data of the gripper and the object during the grasping stage. It can be seen that, the translation and orientation nearly share the same convergence rate. Each object’s angle is tested more than 10 times. The average final error of translation part is less than 3mm. For orientation part, the error is less than 0.05°. The average grasping duration
is around 15s. The three experiments validate the adaptability to variable object poses. After many grasping tests, the tendon-slacking never happens, which verifies the robustness of tendon-slacking prevention. The most important validation is that, the proposed precise kinematics model ensures the accurate gripper's pose, which is the key for successful aerial grasping. Above all, the aerial grasping experiment is a synthetical aerial application, and the AeCoM could fulfill the maneuver requirements with validation of proposed methods.

However, there exists some issues during the experiments, and they should be addressed to improve the AeCoM. The UAV flight controller suffers the disturbance of the manipulator. For instance, the reason why the successful rate of the object’s angle: 80° is lowest, is because the disturbance is the largest. Under this situation, the flight controller cannot maintain precise translational motions, which leads to inaccurate gripper’s translation.

VII. CONCLUSION

This article proposes a novel aerial continuum manipulator with original mechanical design, and complete modeling and control framework for the first time, to the best author’s knowledge. Compared with previous aerial manipulators, the AeCoM has better payload capacity and motion flexibility. The main contributions are to address the issue of tendon-slacking for the tendon-driven continuum robotic arms by designing a tension-feedback controller, and establish a new kinematics model for the proposed aerial system under variable loadings. Comprehensive experiments are designed to validate the performance of the proposed system. Actual aerial flights with the robotic arm’s motion are conducted. The initialization process of the continuum robotic arm is addressed by an automatic initialization method. Payload capacity is evaluated by aerial bending motions. The robotic arm’s controller is validated by consecutive motions. The system shows good accuracy in kinematics modeling and actual applications, and potential in future works. The aerial grasping experiments validate the motion capability during aerial manipulation tasks.

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Fig. 19. The realtime and desired poses of the EE and the object during aerial grasping experiments. (a) Target EE angle: 15°. (b) 50°. (c) 80°.

Fig. 20. The aerial grasping successful rate with the positioning angle of the object. Each object’s angle is tested by 10 times.
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