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Mechanism, structure, and performance of aerial-aquatic biomimetic adhesion robots

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摘　要

在实际应用中，例如长期空中和水下观测、跨介质操作以及海洋生物调查等任务，机器人需要具备水空界面跨越、在两种环境中实现高机动性和长时间工作的能力。本研究的主要目标是构建一综合仿生结构、仿生驱动、仿生传感、运动控制等于一体的新型科学样机，即可游动、飞行、跨介质、在复杂表面上实现两栖吸附、感知吸附和脱附状态的跨介质仿生吸附机器人。基于仿生样机与实验研究，拟回答两个关键的科学问题：鮣鱼吸盘如何实现长时间的复杂表面吸附和吸/脱附状态感知？旋翼机器人如何实现快速、稳定、连续的水空界面跨越以及水下的机动操作？通过这些研究，为具有潜在国防与民用价值的跨介质吸附机器人提供重要理论和关键技术支撑。本文围绕以下几个方面开展相应研究并取得了一定的成果。

1）以生物鮣鱼吸盘为研究对象，利用先进生物形态学和运动学观测手段，首次揭示了生物鮣鱼吸盘鳍片独立腔体、静水压增强的冗余吸附机理和唇圈卷曲剥离脱附机理。基于生物学数据，利用多种先进加工手段，首次设计制作了具有冗余吸附和翻边脱附能力的多材料刚柔耦合仿生吸盘样机。通过科学实验研究了吸盘冗余吸附机理和吸附性能。实验结果表明，仿生吸盘的冗余特征能够在空气中和水下将摩擦应力分别增加 44%和15%，吸附时间分别增加 458%和 206%。吸盘的静水压增强机理使摩擦应力在空气中增加 56%，在水下增加 41%。此外，仿生吸盘相对于传统吸盘在多种复杂表面上具备附着能力，包括狭窄、破损、粗糙、弯曲和湿滑表面。

2）通过观测生物鮣鱼吸盘唇圈，发现了遍布整个唇圈的机械感受器复合体，用于感知吸盘和宿主之间的吸附和脱附。为模仿生物吸盘的感知功能，基于接触通电和静电感应的协同作用原理，设计制作了六个功能层叠加的摩擦纳米发电机式仿生柔性触觉传感器样机。将两个柔性触觉传感器内嵌在吸盘唇圈中，获得具有触觉传感能力的仿生冗余吸附吸盘样机。两个柔性触觉传感器使仿生吸盘在空气和水下都具备卓越的传感性能。吸盘在空气中和水下可感知到的最小压力分别为 0.02 kPa 和 0.1 kPa。为了增强传感器的信号，设计制作了弹片结构功能层，进一步挤压传感器。结果表明，弹片结构在空中和水下分别把信号增大了 32%和 301%。此外，带有传感的吸盘在两种环境中可感知吸附、泄漏和脱附状态，并能够感知冗余吸附。

3）将仿生鮣鱼冗余吸附吸盘和跨介质四旋翼航行器结合，完成了跨介质仿生吸附机器人的设计与制作。该机器人无线可控，可实现远程控制飞行、游泳和附着在空中和

水下的复杂表面上，并且还可以在两者之间无缝跨越。通过分析四旋翼航行器跨越水空介质的动力学特性，发现缩短螺旋桨在水空界面处的转速差对实现旋翼机器人快速跨越介质具有重要影响。设计了一种简单、可复制、大折展比的被动折叠螺旋桨，用以实现机器人快速、稳定、连续跨越介质。这种螺旋桨可以被动地在水下折叠和空中展开。比较了自设计的被动变形螺旋桨和商用螺旋桨在跨介质过程中的性能差别。在油门相同的情况下（50%），自折展螺旋桨机器人跨介质需要耗时 0.54 ± 0.08 s。相比之下，商用和固定展开的折叠螺旋桨分别需要耗时 1.39 ± 0.16 s 和 0.81 ± 0.17 s。机器人可以快速跨越水空界面（约 0.35 s），在跨越过程中保持良好的稳定性（滚转角和俯仰角小于 3°），并且可以实现连续跨越（在 20.3 s 内跨越 7 次）。值得注意的是，相较于悬停状态，机器人的“搭便车”状态在空中和水下分别可将功耗节约 51.7 倍和 19.2 倍。在户外应用测试中，机器人可以在两种介质中运动，记录观测视频，也可以在峡谷溪流和海洋中跨越水空界面并吸附移动物体。

4）提出了一种采用两种不同控制策略的四旋翼平台设计，使机器人能够适应水空差异的运动环境。通过将机器人的两个前臂设计为能够在 0°~270°倾转的矢量推力单元，实现了水下机动运动。建立了机器人空中经典运动模式和水下矢量推进模式的动力学和运动学模型。基于此模型，实现了机器人空中飞行和水下航行的可控机动操作。将带有触觉感知能力的仿生鮣鱼吸盘和矢量推进跨介质四旋翼平台结合，实现了自主吸附的跨水空介质仿生吸附机器人。该机器人同样采用了大折展比的自折展螺旋桨，设计了两层八旋翼构型，来提高跨介质速度，将跨介质时间缩短至 0.16 s。将仿生鮣鱼吸盘的触觉传感和机器人运动控制融合，实现了机器人在空中和水下的自主吸附、感知泄露再吸附以及吸附失败的自救功能。机器人满电状态下，可在空中实现 108 次自主再附着，在水下可实现 534 次。在湖泊中，展示了机器人连续跨越和自主吸附岩石的能力。

关键词：跨介质机器人，仿生软体机器人，仿生吸附，柔性感知，鮣鱼

Abstract

Many real-world applications, such as long-term aerial and underwater observation, cross-medium operations, and marine life surveys, require robots with the ability to cross between the air-water boundary, perform high maneuverability in two environments, and maintain long-term work. The primary objective of this study is to implement an aerial-aquatic hitchhiking robot that can swim, fly, cross medium, attach to complex surfaces in both air and water, and sense attachment/detachment states. This research aims to address two scientific questions: 1) how does the remora adhesive disc achieve long-term adhesion on complex surfaces, and sense attachment and detachment? 2) how can rotor-based aerial-aquatic robots achieve rapid and stable transitions between water and air, and agile underwater maneuvering? Through these investigations, this research provides essential theoretical foundations and critical technological support for the development of cross-medium adhesion robots with potential applications in both defense and civilian domains. This paper presents research findings and achievements in several key areas:

1) Using morphological and kinematic observation methods, we revealed, for the first time, the independent lamellar compartments, hydrostatically enhanced, redundant adhesion mechanism, and the lip curling detachment mechanism of the remora adhesive disc. Based on biological data and various manufacturing methods, we designed and fabricated a multi-material, rigid-soft coupled biomimetic disc prototype with redundant adhesion and curling detachment capabilities. Through experiments, we have explored the redundant adhesion mechanism and adhesive performance of the disc. The results indicate that the redundant features of the biomimetic disc can increase frictional stress by 44% and 15%, and adhesion time by 458% and 206% in air and underwater, respectively. The hydrostatically enhanced mechanism increases frictional stress by 56% in air and 41% underwater. Furthermore, the biomimetic disc demonstrated the capability to adhere to a variety of complex surfaces, including narrow, incomplete, rough, curved, and biofouling surfaces, surpassing traditional suction cups.

2) Using a light microscope, we observed micro mechanoreceptor complexes embedded in the remora disc’s soft lip used to sense attachment and detachment to hosts. To mimic the biological mechanoreceptor complex of the remora disc, we designed and fabricated a self-powered and flexible bio-inspired tactile sensor (FBTS) based on the triboelectric nanogenerator. The FBTS structure contains six flexible functional layers. Based on the morphological features of the natural remora disc, we designed and fabricated a biologically

inspired prototype that has two flexible tactile sensors embedded in the disc lip for sensing attachment and detachment. This biomimetic disc performs outstanding sensing performance in both air and underwater environments. The disc can sense pressures as low as 0.02 kPa in the air and 0.1 kPa underwater, respectively. We also designed the functional layer of the elastic sheet structure to enhance the tactile signal of FTBSs. Our experiments have demonstrated that the elastic sheet structure of the biomimetic disc can increase the signal by 32% in air and 301% underwater. Furthermore, the disc with FBTSs can sense the redundant attachment, leakage, and detachment states in two different environments.

3) By combining the biomimetic remora disc with a cross-medium quadrotor, we implemented an aerial-aquatic hitchhiking robot. This untethered robot is self-contained for flying, swimming, and attaching to surfaces in both air and water and that can seamlessly move between the two. We analyzed the dynamic characteristics of the quadrotor during the water-air transition. This analysis identified the shortened rotor speed difference at the water-air interface as a critical factor in achieving rapid transition for rotorcraft robots. To achieve rapid, stable, and continuous transition of the robot, we designed a simple, replicable, and high-folding-ratio morphing propeller. This propeller can passively fold underwater and unfold in the air. We compared the performance of self-designed passive propellers with commercial propellers during water-to-air transition. Under the same throttle percentage (50%), the robot with self-folding propellers achieved transition in 0.54 ± 0.08 s. In contrast, robots with commercial propellers and self-folding propellers fixed in an unfolded state took 1.39 ± 0.16 s and 0.81 ± 0.17 s, respectively. The robot can rapidly cross the water-air interface (0.35 s), maintain excellent stability during the transition (with roll and pitch angles below 3°), and achieve continuous transitions (7 times in 20.3 s). Importantly, the "hitchhiking" state of the robot significantly reduces power consumption, by 51.7 times in the air and 19.2 times underwater compared to hovering. In field tests, the robot can record videos in both media, transit the water-air boundary in a mountain stream and the ocean, and adhere to a moving UUV.

4) We proposed a design scheme for a quadrotor platform that employs two different control strategies to adapt to the distinct motion environments of water and air. The robot's two forearms have been designed as vector thrust units capable of rotating 0° ~ 270° for underwater motion. We have established dynamic and kinematic models for the robot's classical aerial flight mode and underwater vector thrust mode. Based on these models, we have achieved controllable maneuvering operations for the robot in both aerial flight and underwater navigation. We developed an autonomous attachment aerial-aquatic hitchhiking robot by

integrating a thrust vectoring quadrotor equipped with the biomimetic remora sensing disc as a hitchhiking device. This robot also employs high-folding-ratio morphing propellers and features dual propellers and motors in each vehicle arm to enhance transition speed, achieving a reduced transition time of 0.16 s. By integrating the tactile sensing capabilities of the biomimetic remora disc with robot motion control, we have realized autonomous attachment, perception of leakage and re-attachment, and self-protection after attachment failure in both air and underwater environments. The robot, when fully charged, can achieve autonomous re-attachment 108 times in the air and 534 times underwater. In a natural lake environment, we have demonstrated the robot's continuous transitions and autonomous adhesion to a rock surface.

Keywords: Aerial-aquatic robots, Biomimetic soft robots, Biomimetic adhesion, Flexible sensors, Remora