ANIMAL ROBOTS

Perching and resting—A paradigm for UAV maneuvering with modularized landing gears

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Perching helps small unmanned aerial vehicles (UAVs) extend their time of operation by saving battery power. However, most strategies for UAV perching require complex maneuvering and rely on specific structures, such as rough walls for attaching or tree branches for grasping. Many strategies to perching neglect the UAV's mission such that saving battery power interrupts the mission. We suggest enabling UAVs with the capability of making and stabilizing contacts with the environment, which will allow the UAV to consume less energy while retaining its altitude, in addition to the perching capability that has been proposed before. This new capability is termed "resting." For this, we propose a modularized and actuated landing gear framework that allows stabilizing the UAV on a wide range of different structures by perching and resting. Modularization allows our framework to adapt to specific structures for resting through rapid prototyping with additive manufacturing. Actuation allows switching between different modes of perching and resting during flight and additionally enables perching by grasping. Our results show that this framework can be used to perform UAV perching and resting on a set of common structures, such as street lights and edges or corners of buildings. We show that the design is effective in reducing power consumption, promotes increased pose stability, and preserves large vision ranges while perching or resting at heights. In addition, we discuss the potential applications facilitated by our design, as well as the potential issues to be addressed for deployment in practice.

INTRODUCTION

With recent advances in lightweight, low-power sensor technology and onboard computation, unmanned aerial vehicles (UAVs) are now engaging in missions with an unprecedented degree of autonomy (*1*–*3*). Onboard sensors such as cameras, ultrasonic sensors, and accelerometers not only provide advanced perception capabilities that allow increasingly complex missions but also enable more powerful control methods (*4*–*8*). Even commercial off-the-shelf (COTS) UAVs can reliably fulfill missions such as aerial videography, autonomous surveillance, object delivery, and construction site inspection (*9*–*13*) and are deployed in crisis response to provide on-site measurements (*2*, *14*–*16*) or set up ad hoc data networks (*17*).

Autonomous UAVs are often deployed to conduct long-duration missions that require watching an area on the ground from heights for an extended period of time, such as in an autonomous surveillance task (*12*, *18*). For this reason, energy consumption is one of the primary concerns in the operation of lightweight UAVs because mission duration is limited by battery power. Because UAVs require constant motor action to create lift to stay in the air, more energy-efficient control and aircraft design are therefore of high interest to reduce the energy consumption during flight (*19*–*24*). However, the most effective way of saving energy is to directly reduce the required lift during execution of the mission.

Exploiting contacts to save energy

In this work, we try to learn from nature and take inspiration from the behavior and anatomy of birds and bats. However, we propose a design that is simpler and more optimized for the specific task of saving energy than what we observe in nature. Figure 1 displays several ways in which animals with powered flight have adapted to temporarily exploit contacts with structures in their habitat for saving energy. For example, birds can be observed placing their feet on supports while still flapping their wings, and bats are known to hang upside down while grasping suitable surfaces. In all of these cases, some suitably shaped part of the animal's foot interacts with a structure in the environment and facilitates that less lift needs to be generated or that power flight can be completely suspended.

Our goal is to use the same concept, which is commonly referred to as "perching," for UAVs. Perching requires attaching and detaching from a structure in the surroundings on command and relies on the availability of certain structures in the surroundings, such as tree branches. It is therefore limited to a small set of mission environments; when the perching location does not provide a good view range, it will result in mission interruptions. For addressing the problem of allowing UAVs to reduce their power consumption in a mission, we propose to enable UAVs with the capability of making and stabilizing contacts with the environment to obtain force support. With this capability, UAVs require less lift generated by the motors and can save energy. Moreover, it enables UAVs to be able to exploit a much larger range of structures in the environment to conduct missions without interruptions. We term this kind of action "resting" (Fig. 1, left and right). Perching or resting on elevated locations allows continuation of a large range of UAV missions with reduced, or even suspended, motor action and therefore extends the UAV's operation time and allows long-duration missions, such as in the most common perch-and-stare missions (*25*). Additionally, perching and resting remove degrees of freedom from the UAV's motion and can therefore reduce the required attention from operators and can improve safety.

The need for perching capabilities in UAVs has led to research in a wide range of different forms of landing gears (*26*–*44*), control for the required flight regimes, and the generation and optimization of

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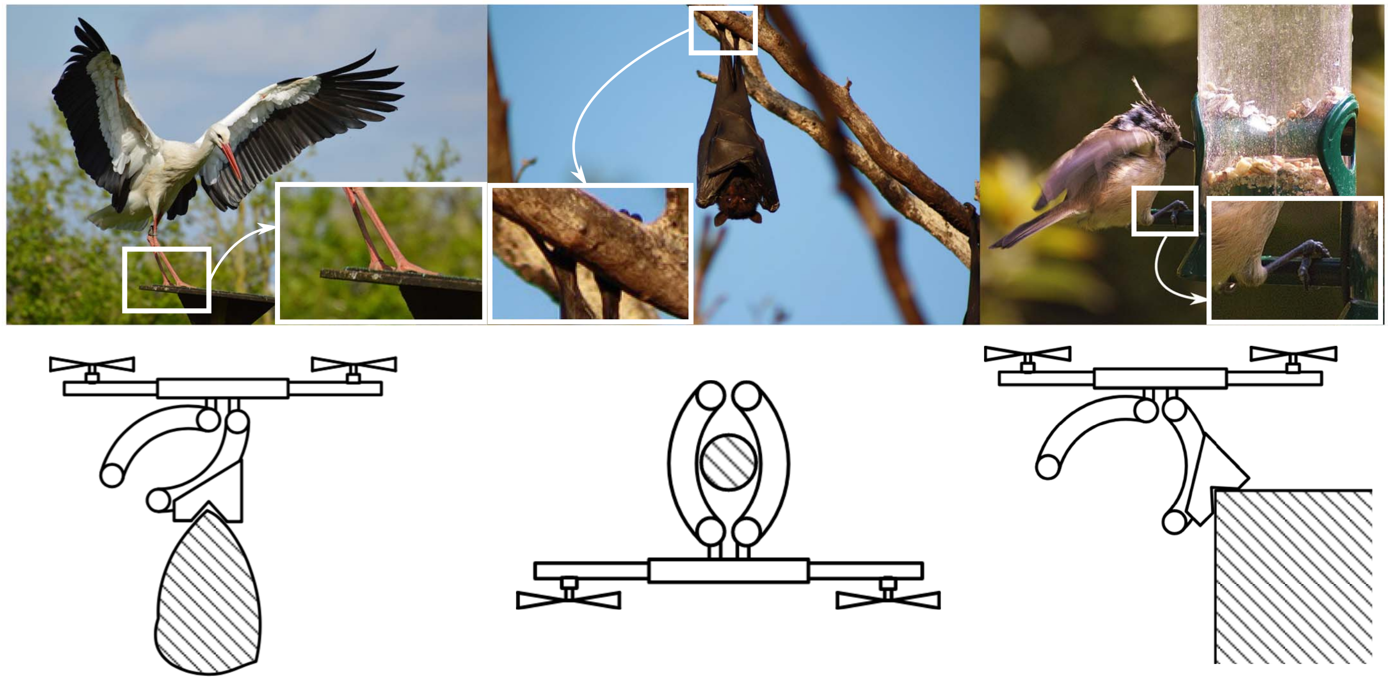

Fig. 1. Example perching and resting actions in nature. Flying animals such as birds or bats often make use of structures in the environment to save energy. In choosing, they select locations that can be approached and evacuated by simply maneuvering in the air while still allowing them to execute a mission such as observing the environment or looking for prey.

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approach trajectories (*30*–*32*, *37*, *38*, *45*–*47*). Surface contacts were established and maintained with dry adhesive technology, such as electrostatic surfaces (*41*–*43*) or fibers (*44*). A collection of small needles were used for perching on rough surfaces (*26*–*31*) or combined to form bioinspired claw-like grippers (*33*). Also, multiple tensile anchors were launched to fixed structures (*48*) to mechanically stabilize the UAV for high-accuracy operation in a three-dimensional (3D) workspace. Other UAV-mounted grippers took design inspiration from the feet of songbirds for perching on branch-shaped structures (*37*–*40*). Furthermore, grippers were used to attach to flat surfaces (*32*, *46*) and, in some cases, also served as landing skids when opened (*36*). In general, passive and compliant grippers can wrap around structures (*34*, *39*–*41*), whereas actuated grippers can actively grasp a structure to attach the UAV (*33*, *36*).

Challenges

Approaches based on dry adhesive (*41*–*44*) or small needles (*26*–*31*) have only been demonstrated for extremely lightweight UAVs and require specific UAV design to allow proper positioning of the landing gear for perching. Therefore, these approaches are difficult to adapt to COTS UAVs or UAVs that carry a heavy sensor payload, such as a high-resolution camera. Also, although avian-inspired grippers can be mounted on COTS UAVs, most gripper-based approaches are limited to perching on cylindrical structures of a certain diameter (*36*).

As another very important component for perching, control has to address a challenging problem because the UAV needs to be positioned close to a structure. Different from flight in open space, this is often done with flight regimes involving high angle of attack (*47*), post stall (*45*), or aggressive (*32*, *46*) maneuvering to bring the landing gear to the required attitude and location while the UAV reaches a flight condition that allows safe contacting on the structure. In bioinspired approaches, this can be done directly from feedback without optimizing the flight trajectory explicitly before the flight (*37*, *38*). For maneuvering while in contact with a pivot point on a structure, dynamic modeling of the different flight phases is necessary (*49*).

However, flight regimes for attaching and detaching are, in many cases, complex and are not covered by control for COTS UAVs. For instance, approaches that perch on walls and have the landing gear mounted below the UAV have to fly toward the wall and turn the bottom side forward for attachment (*26*–*32*, *46*). Failure to attach will result in a critical flight condition close to an obstacle. These risks are shared with approaches that use a high angle of attack (*47*) and post stall (*45*) maneuvers for perching. Perching on walls can also require a mechanism-supported takeoff strategy that puts the UAV in a critical flight condition after detachment (*26*).

Many approaches are not focused on continuing the UAV's mission and can therefore lead to mission interruption when perching. For instance, in approaches that rely on surfaces for perching, the UAV has to comply to the surface's orientation (*26*–*32*, *46*), which might obstruct sensors or communication devices. As a result, it is still challenging to enable perching capabilities in COTS UAVs under a wide range of circumstances without disrupting the mission or requiring risky and complex maneuvering that involves critical flight conditions.

A new paradigm for perching and resting

As mentioned above, we observed in nature that (perching) birds and bats have adapted to their habitats by developing prehensility and claws in their feet, which allows them to use a large variety of structures for support when perching (see Fig. 1). Instead of directly imitating, for instance, the feet of perching birds (passerine birds), we propose a simplified and specialized solution for COTS UAVs. On the basis of four design principles, we designed a modularized and actuated landing gear framework for rotary-wing UAVs consisting of an actuated gripper module and a set of contact modules that are mounted on the gripper's fingers. The gripper module was mounted on the bottom side of the UAV and, for its weight and size, was compliant with a large range of COTS UAVs. Unlike previous approaches with grippers (*37*–*40*), our approach was not limited to cylindrical structures and did not require complex attachment maneuvers, such as a sideways approach (*32*, *46*).

If a horizontal surface was available, the gripper module was opened and the stiff fingers were used as landing skids, similar to a bird landing on a flat rooftop. If a cylindrical structure was available, the UAV approached it from above such that the gripper module could grasp the structure, after which all motors could be suspended. This was directly inspired by how birds land on branches of trees onto which they then hold. For other types of structures, such as edges or corners of a building, strut, bar, or street sign, we relied on modularization, allowing us to flexibly design and fabricate contact modules that matched the specific structure. Through gripper actuation and position control, we then brought a suitable contact module to rest on the structure, and all or a part of the UAV's weight was supported by the structure, reducing the required lift. This modularization substantially increased the range of possible structures that can be exploited for perching and resting as compared with avian-inspired grippers. Although not inspired by nature and much more simple than the foot of a bird, the stiff fingers and contact modules were easier to manufacture and more robust and durable than avian-inspired grippers with several joints per finger.

Takeoff and landing are critical phases in a flight; for example, pigeons show complex patterns of wing strokes for acceleration and deceleration during maneuvers (*50*). Although we took inspiration from how birds and bats rest, we did not imitate their maneuvering for landing or taking off because the UAV as a rotary wing aircraft has substantial different flight characteristics from birds and bats with flapping wings. In contrast to previous approaches (*32*, *37*, *38*, *45*–*47*), we developed an approach that relied on position control and reference poses only, without requiring complex control strategies. For perception, we present a proof-of-concept method that identified suitable structures for perching and resting from point cloud data of the environment.

Overall, we investigated four fundamental questions of UAV maneuvering in terms of the exploitation of external contacts: (i) how to design landing gears to facilitate UAVs to exploit contacts for perching and resting, (ii) how energy consumption and pose stability are affected by perching and resting, (iii) how the mission-relevant view ranges of UAVs are affected by different perching and resting actions, and (iv) the use cases and limitations of the proposed paradigm.

In experiments, we mounted our landing gear framework on a COTS UAV and demonstrated the efficacy of our design in enabling the desired perching and resting capabilities in a controlled laboratory environment. The experiments included perception of and perching and resting on different structures. During the experiments, the UAV was globally localized with an external measurement system. In this setting, we evaluated power consumption and pose stability during perching and resting for empirical comparison with hovering. Furthermore, we qualitatively studied the view ranges of different perching and resting actions on locations at heights and discuss other potential usage in terms of the features enabled by perching and resting. Our experiment results show that the proposed paradigm not only reduces energy consumption but also enables UAVs to exploit external contacts with a variety of structures to facilitate mission execution, which, to the best of our knowledge, has not been extensively studied.

RESULTS

Our modularized and actuated landing gear framework is designed to be flexible and accommodate a wide range of applications. To demonstrate and evaluate the principles and efficacy of our design, we present a proof-of-concept study in which we designed and fabricated a landing gear for a DJI F450 quadrotor platform and tested the resulting perching and resting capabilities in a number of scenarios with different structures. Because most recent UAV applications involve load-carrying for videography or surveillance, we evaluated the perching and resting states in terms of (i) power consumption, (ii) pose stability, and (iii) view ranges.

We fabricated the gripper module's base and fingers using carbon fiber to keep the landing gear rigid and lightweight. The contact modules were 3D printed using the soft TangoBlackPlus material to facilitate contact compliance and stability for a wide range of environments. The weight of each part of our landing gear framework is listed in table S1. In the experiments, the environment was perceived using an externally placed Kinect One sensor, which provided point clouds in which we detected structures that allowed perching and resting. Once contact locations in the environment were identified, as shown by colored points in Figs. 2 and 4, the UAV was autonomously navigated on the basis of the localization provided by a VICON system. An example laboratory setup for our experiments is shown in Fig. 2.

Landing gear design

In this section, we first describe the design principles of the proposed modularized landing gear framework. On the basis of the principles, we demonstrate our example design and evaluate its performance.

Principles of landing gear design for perching and resting with COTS UAVs

To enable perching and resting under various circumstances while keeping the design versatile, we proposed to design landing gears obeying four principles:

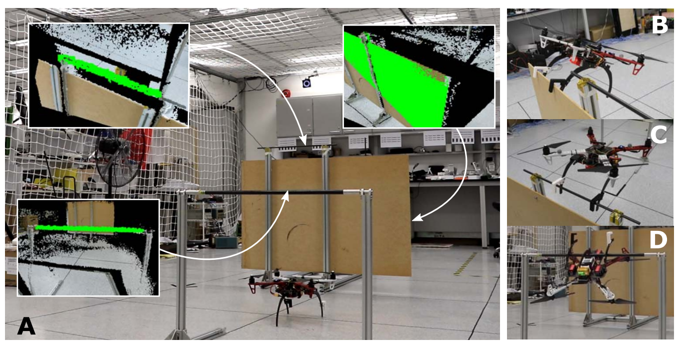

Fig. 2. Example actions with vision-based perching and resting location detection. (**A**) Laboratory environment and detected perching and resting locations. (**B**) Perching by hooking on a thin board (P_H). (**C**) Resting by hooking on a stick (R_H). (**D**) Perching by grasping around a stick (P_G).

1) The landing gear should be usable for landing on flat surfaces, mirroring the capabilities of most standard landing gears for COTS UAVs. This allows the UAVs to land and take off as usual COTS UAVs.

2) The landing gear should allow the UAVs to grasp or hook around structures of different scales. This allows the UAVs to turn all rotors off when perched

3) The landing gear should allow the UAVs to rest on different structures to provide lift support in the vertical direction. This allows the UAV to slow down or completely stop some of the rotors when resting by establishing stable contacts with the environment.

4) The landing gear should be mountable on a COTS UAV and be minimalistic in hardware, actuators, and control. This allows the user to design and replace parts of the landing gear without the need of reprogramming when working in different scenarios.

Following the principles, we demonstrate an example design consisting of an actuated gripper module that features principles 1, 2, and 4 and a set of contact modules that features principles 3 and 4.

Actuated gripper module

The actuated gripper module consists of servomotors, a set of fingers, and a base platform that attached to the bottom of the UAV. Our landing gear design for the DJI F450 UAV with three fingers is shown in Fig. 3. On the base platform, the three servomotors were installed to actuate open and close motions of the fingers. To ensure sufficient grasping forces, the three servomotors were adopted to actuate the fingers separately. However, the motors were controlled jointly for open and close actions with only one degree of freedom. In practice, all fingers can be actuated by a single motor as long as the provided torque is sufficient for the grasping actions. When the gripper was opened, the fingers enabled normal landing and takeoff from the ground because the fingertips were in level position under the UAV.

As seen in Fig. 3, the size of the landing gear is approximately identical to the UAV's dimensions. This enables the UAV to grasp structures of up to 0.2 m in radius. However, deciding on the dimensions of the gripper module involves trade-offs in the size of potential perching structures, the gripper weight, undesired aerodynamical side effects, and collision-free maneuvering. A larger gripper can accommodate larger structures but can lead to loose contact for small structures. Our design made finger replacement easy, and it is recommended to design the fingers in appropriate sizes to achieve the tasks while avoiding undesired side effects. Additionally, the design of the gripper fingers should guarantee that it makes a closed loop when in close position, which ensures perching ability on all structures within the scale of the landing gear.

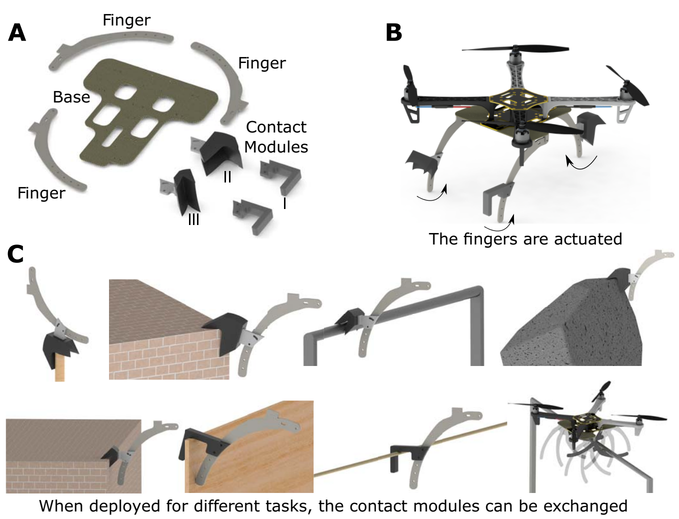

Fig. 3. An example landing gear design for DJI F450. (**A**) Example of the modularized landing gear design consisting of a base, three fingers, and three different contact modules. (**B**) Example of the installation of the designed modules on a DJI F450 platform. (**C**) Example perching and resting actions using different contact modules or the actuated gripper module.

Contact modules

According to the design principles, we equipped the UAV with different contact modules that were easy to use, design, and fabricate. Inspired by the claws of birds, we designed the contact modules such that they were able to stabilize the UAV with different structures in the environment by contacting their modeled side, which acts similar to claws to hold onto small or thin structures. As shown in Fig. 3, contact modules were installed at the distal ends of the fingers, making them accessible to structures below the UAV. For resting, the gripper module was actuated to bring the contact module to the desired pose. This could be an open pose for contacts on one side of the UAV (Fig. 4A) or a closed pose for contacts below the center of the UAV (Fig. 4B). The contact modules themselves were not actuated for actively stabilizing the contacts. Instead, their shapes were adapted to achieve stable contacts against certain structures. On the basis of the minimalistic and modular design principles, the contact modules were exchangeable to provide more contact possibilities with a large variety of geometries.

In this work, we exemplify a few contact module designs that were based on the concept of contact primitives and fingertip surface optimization (*51*). The algorithm synthesized contact modules based on a set of example structures. As long as the provided examples sufficiently represented potential contact structures, the synthesized contact modules were able to stabilize the contacts. Figure 3 shows two contact modules (II and III) that were synthesized by the algorithm. Additionally, similar to claws that birds use to grasp and perch, we designed another L-shaped contact module, which, together with the finger, created a U-shaped claw. As shown in Fig. 3, this design

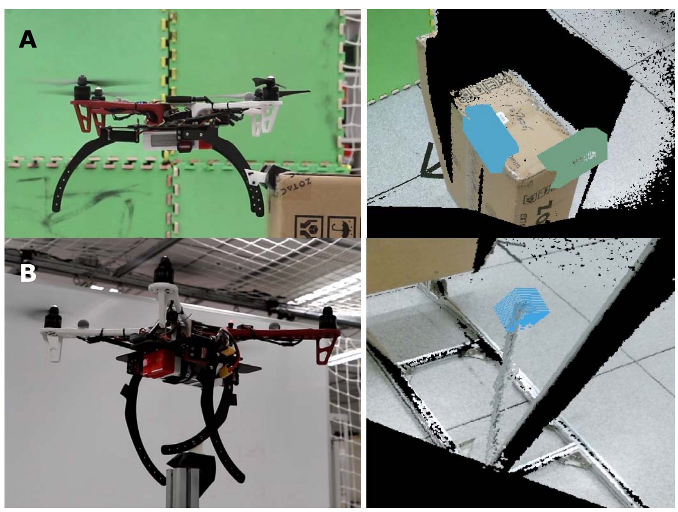

Fig. 4. Example resting actions with vision-based perching and resting location detection. (**A**) Resting on a box's edge (R_E). (**B**) Stand-resting on a stick (R_S).

allowed perching on thin structures onto which a UAV can hook itself using gravity.

Saving power by reducing motor action

In this work, we exemplify five perching or resting actions using the experimental UAV for demonstration and evaluation. As seen in Figs. 2 and 4, the actions were perching by hooking (P_H), perching by grasping (P_G), resting by hooking (R_H), resting on an edge (R_E), and stand-resting on a stick (R_S).

Power consumption is one of the major concerns for many UAV applications, and the main goal of our design was to save battery power by reducing motor action for generating lift. For this reason, we analyzed energy consumption in examples of perching and resting and compared them with the energy consumption while hovering in the air or above the floor.

If the UAV was perching by grasping around a structure (P_G) or hooking on a thin structure (P_H), as seen in Fig. 2, its weight was fully supported by the structure, and all the rotors could be turned off. Therefore, the energy consumption was 0.

When using a contact module below the center of the UAV for resting, as seen by the action R_S in Fig. 4, all the rotors still needed to be used for maintaining the balance. However, the rotors could be markedly slowed down because the load was mainly supported by the structure. When using contact modules for resting on a structure below the side of the UAV, as shown by the actions R_E in Fig. 4 and R_H in Fig. 2, the UAV had to only maintain two degrees of freedom, which were the rotation about the contact line and sliding along the contact line. In those cases, two rotors could be completely turned off.

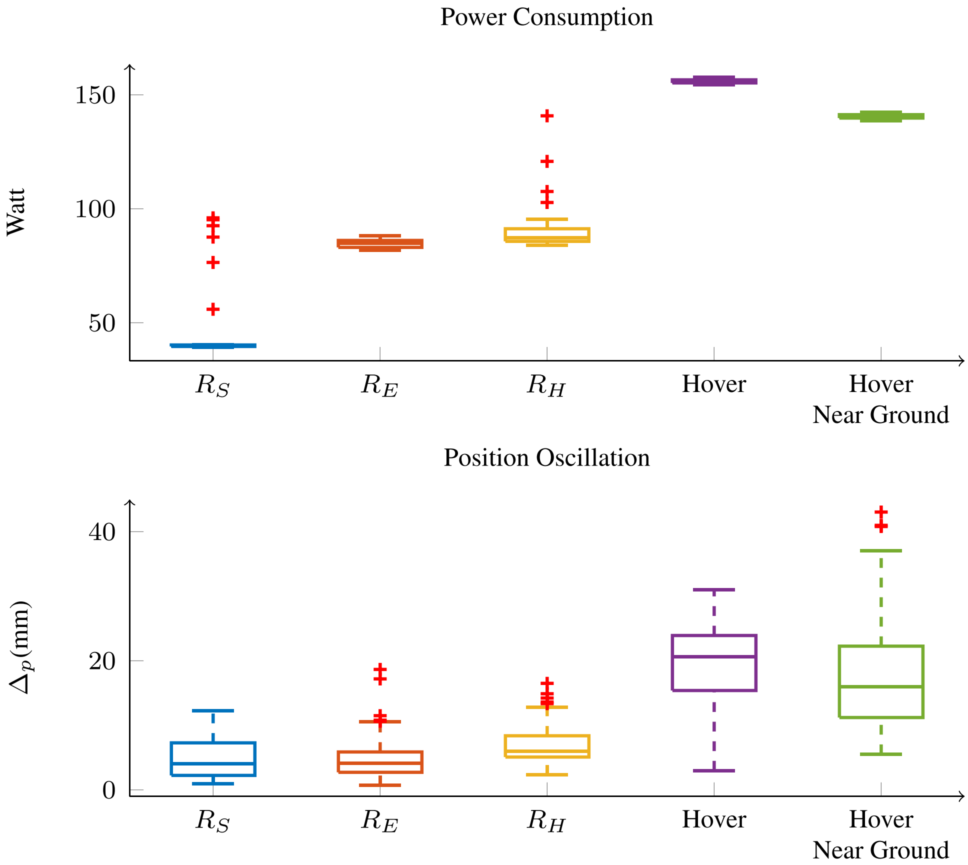

Fig. 5. Power consumption and stability evaluation results. For measuring the power consumption, we took the measurement directly from the motors without considering the power consumed by other electronics. On each box plot, the central mark indicates the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. The whiskers extend to the most extreme data points not considered outliers, and the outliers are plotted individually using the "+" symbol.

Empirical results are reported in Fig. 5. The power consumption data were recorded from the point when the UAV had stabilized itself and ended when the UAV took off again. As can be seen from the figure, the stand-resting action R_S consumed the least energy because almost all the load was supported by the contact. When resting on the box edge R_E or on the stick R_H, power consumption was higher, which was up to about half of the energy consumption of the hovering action. It is worthwhile noting that these two resting actions consumed a bit more power than half of the hovering. This is because the UAV needed to counteract the ground effect when it was very close to other objects. Last, we could see that, when hovering near ground, due to the ground effect, the UAV consumed a little less energy than hovering in the air. In comparison with hovering in the air, R_S, R_E, and R_H saved 69, 46, and 41% power consumption, respectively.

Evaluating stability and view range

For many applications such as videography, surveillance, or object delivery at heights, stable positioning of the UAV over a period of time is necessary. For this reason, we evaluate position oscillation Δ_p with respect to a reference location $\bar{p} = (\bar{x}, \bar{y}, \bar{z})$ for different perching and resting scenarios. For this, we define $\Delta_p = \frac{1}{T}\sum_{i=1}^{T}\sqrt{(x_i-\bar{x})^2+(y_i-\bar{y})^2+(z_i-\bar{z})^2}$, where ($x_i$, y_i, z_i) is the location sampled at time i, $1 \le i \le T$. Because the UAV's position was passively determined when all rotors were turned off, we only evaluated the position oscillation for resting actions when the stability was actively determined by the control of rotors.

As reported in Fig. 5, hovering results in oscillation were within a small range of about 2 cm. However, resting was even more stable and maintained the desired pose within about 5 mm. By checking the standard deviations, we could see that the standard deviations of resting were less than half of those of the hovering actions. These results show that resting can provide more stability while at the same time reducing power consumption.

Especially in perch-and-stare missions, the UAV's view range is a crucial concern when it is tasked to stare or watch over a certain area. However, landing on a flat elevated position such as a rooftop can significantly reduce the UAV's view range. Figure 6 shows how the rooftop occludes most of the view ranges below when a UAV lands on it. Compared with that, perching or resting as offered by the modularized landing gear framework can improve the view range. In

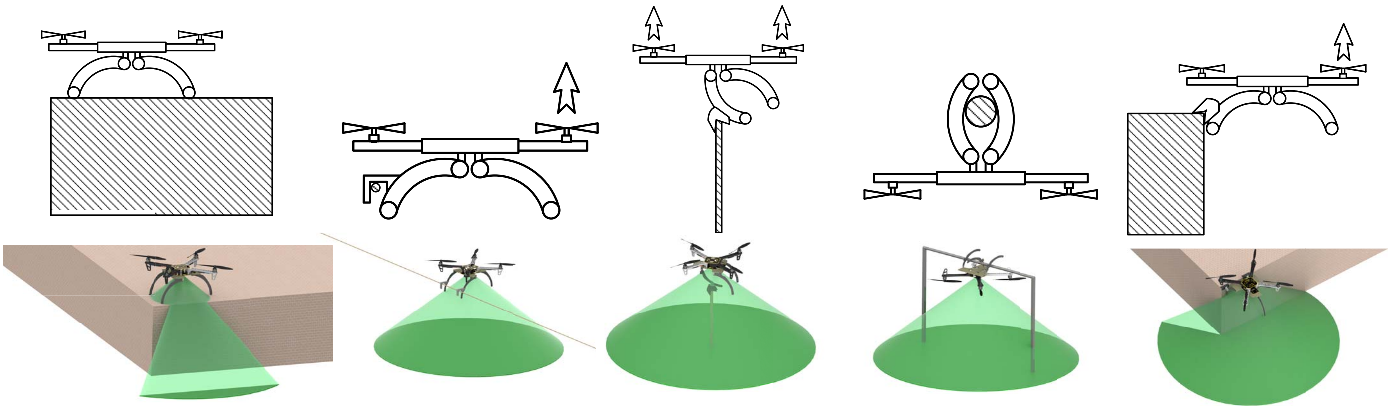

Fig. 6. Example view ranges of different perching and resting actions. The top row shows various perching and resting actions, with arrows indicating which rotors are still working for generating lift. The bottom row shows the corresponding view ranges rendered by green cones.

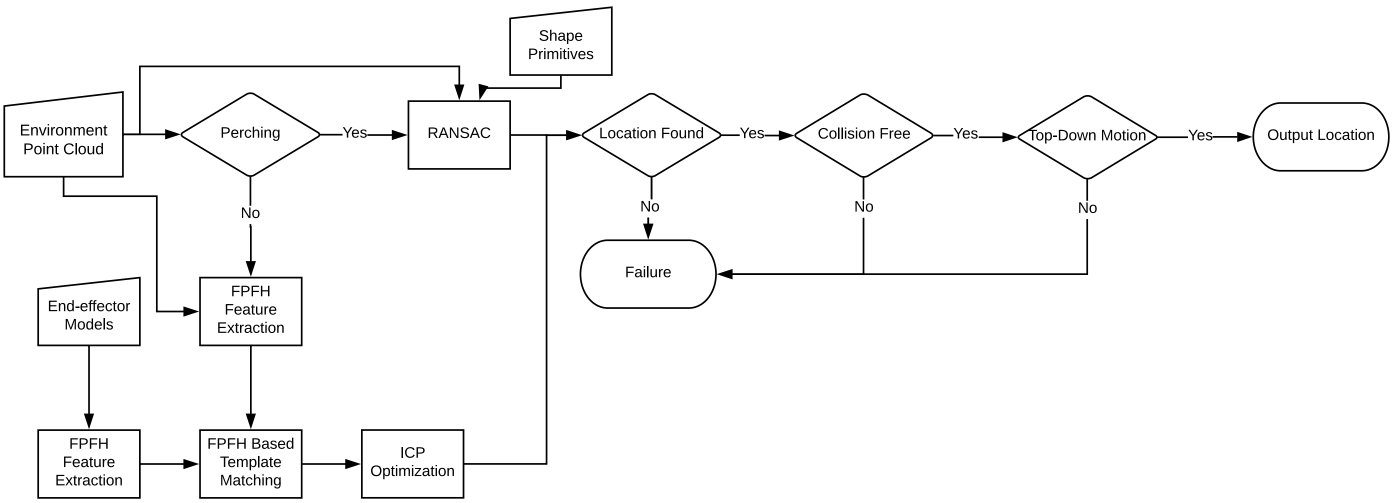

Fig. 7. Flowchart of the hybrid system for perching and resting location detection.

most cases, the UAV could fully observe the area below it without any occlusions. An exception was seen when a UAV rested on the edge of a building, which occluded about half of the view below. Nonetheless, it was still much better than a normal roof landing.

Upon using different perching or resting actions, the onboard camera could be configured accordingly to optimize the view. For example, when perching on a stick by using the actuated fingers to grasp, the UAV will finally be stabilized after it turns over around the stick and stops all its rotors. Hence, unlike most UAVs, which have the camera installed below the main frame, the camera, or an extra camera, should be installed on top of the UAV to achieve the view range when the UAV turns over and faces down.

DISCUSSION

In this section, we first give a brief summary of what has been proposed and evaluated. Thereafter, we discuss the limitations and implementation concerns of our design, the concerns in pose stability and energy consumption in relation to our paradigm, and the use cases of the proposed design framework.

In this work, we focused on the problem of enabling perching and resting for rotary-wing UAVs. First, we proposed to enable UAVs with the capability of making and stabilizing contacts with the environment so as to obtain force supports from the contacts to be able to consume less battery energy while retaining the heights. For this, we developed a design framework of modularized and actuated landing gears consisting of an actuated gripper module and customized contact modules. The goal was to permit lower power consumption, better stability, and larger view ranges when the task was to be executed at fixed locations at heights. Following the four design principles, we designed an example landing gear for a DJI F450 quadrotor. The example design is composed of a base platform, three actuated fingers that were fabricated using carbon fibers, and three customized contact modules that were 3D printed using soft materials. The design resembles the basic functionalities of normal landing gears allowing landing and takeoff actions and is lightweight for the UAV to carry on board while not introducing much more extra power consumption.

We validated the example design by demonstrating perching and resting under laboratory conditions, such as perching by grasping and hooking, resting on an edge or stick, and stand-resting on a stick. The stability and power consumption of demonstrated actions were evaluated, and the results indicate that the featured actions can significantly reduce the power consumption while providing better stability comparing with normal actions. Additionally, we have

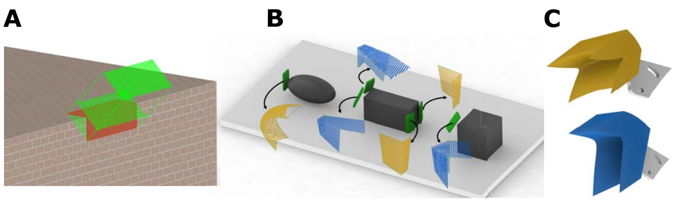

Fig. 8. Example contact area extraction for automatic contact module design. (**A**) Extraction of a contact area (red) based on the specified contact pose and size. (**B**) Shape primitives (black) and extracted contact areas (clustered in blue and yellow) used in the contact module design in this work. (**C**) Contact modules designed in terms of the clustered contact areas.

qualitatively shown that the featured actions provide much larger view ranges when working at heights, which can hardly be achieved by normal landing actions.

Limitations and implementation in practice

In this work, our experimental quadrotor was not equipped with onboard vision capability. The perching and resting locations were detected on the basis of the point cloud obtained by an external Kinect One sensor beforehand, and the UAV was navigated by a VICON system in the laboratory environment. In practice, when maneuvering a UAV in outdoor environments, the onboard visual perception is important to help the human operator to navigate or to enable the UAV to be more autonomous. When a UAV is tasked to autonomously execute perching or resting actions, an onboard visual sensor is required to enable the UAV to understand the environment, as well as to detect the locations where desired actions can be applied. As will be described shortly, given that the modularized landing gears were flexibly customized for accommodating a certain range of task requirements, the vision algorithms can be designed using template-based approaches that match geometrical features between the environment and the designs. Nevertheless, the vision-based detection approach is intrinsically limited in that it is not easy to acquire physical properties of the environment, such as the rigidity of the detected locations, which can affect the action stability. For addressing this problem, learning-based algorithms can be adopted to predict the physical properties. More reliably, active perception algorithms can be developed to conduct physical estimation by enabling the UAV to actively interact with the environment; for example, a UAV can use its contact modules to touch and press certain locations to acquire knowledge, which can potentially be obtained by additional sensors installed on the contact modules.

Additionally, in our experiments, our control strategy is to always navigate the UAV to a point above the perching or resting locations and then execute the action from top-down. However, in many tasks in reality, one can imagine a UAV working in confined environments, in which the perching or resting actions cannot be executed without a trajectory planning algorithm. As discussed in (*38*, *52*), we could enable the UAV with trajectory planning to perch or rest in more difficult scenarios by bringing the UAV to the desired location without the top-down motion constraint. For instance, a UAV could perch on a tree branch by approaching it from the side and grasping it with the fingers when the region above that tree branch is occluded.

Pose stability and energy consumption

As the main goals of the proposed paradigm, pose stability and energy consumption have been evaluated using an example design in a laboratory environment. The experimental results have shown that both perching and resting actions can significantly reduce the power consumption by exploiting force support from external contacts. In addition, using the same flight controller, we have seen that pose stability has been improved when external contacts were made. This can be explained by the fact that, when contacts were made between the contact modules and external structures, the degrees of freedom of the UAV's movement were reduced. Hence, the potential external disturbance was reduced, and more importantly, the flight controller could focus on balancing only the remaining degrees of freedom, mitigating the trade-off of keeping pose stabilities between different moving dimensions.

Nonetheless, we can foresee a variety of factors that can affect these two performance concerns. When a UAV is tasked to work in outdoor environments, wind disturbance and other aerodynamic uncertainties can be a major factor that affects pose stability. In this case, the flight controller will have to regulate the actuation inputs more intensively to keep the stability at a similar level, resulting in increased energy consumption. Moreover, the rigidity or mobility of contact locations can be another concern that affects the pose stability. For example, when resting by making contacts at a thin tree branch, although the UAV can gain force support to reduce energy consumption, stability is more difficult to keep because of the passive movement of the contacts, and the UAV will consume more motor energy in comparison with making contacts at rigid locations. To reduce the effect of physical uncertainties and to improve the energy performance, although not included in this work, we plan to design a tilt-pan connector between the main body of the UAV and the modular landing gear. By mechanically decoupling the movement of the UAV's main body from the landing gear or by actively compensating the disturbances at the connector, the pose stability can be further improved. Limited by the scope of this study, we leave this development to our future work.

Use cases

A UAV with perching and resting capabilities may enable many applications that are not possible otherwise. Besides that perching and resting can provide lower power consumption, better stability, and larger view ranges in many cases, which are very useful for perch-and-stare applications, the physical interaction with the environment enabled by such actions may additionally empower many more applications. For example, in aerial grasping (*53*–*55*), the maximum load is limited by the power provided by the rotors. However, once a UAV is perched, it will be able to lift markedly larger loads without requiring any power from the rotors.

When delivering objects to workers at heights, a UAV can perch or rest at some location near the worker for object pickup, or it can carry a pair of pulley and rope to perch at a certain location, such that object delivery can be achieved from both ends of the rope. While resting at the edge of a windowsill, a UAV will be able to deliver objects to someone inside, without the need to keep the rotors at the window side still working, so as to reduce the risk for humans to interact with a UAV. Overall, the ability of making contacts by resting or fixing itself by perching at heights may empower many applications that are related to load-lifting and that demand interaction.

MATERIALS AND METHODS

In addition to the design of the proposed modularized landing gears, this section briefly describes how to enable a UAV with such landing gears to execute the perching and resting actions in reality. Concretely, we introduce how we implemented the vision algorithm to detect perching and resting locations, how the UAV was controlled, and how to automatically design contact modules based on example contacts.

Perching location detection and navigation

As the main focus, we concentrated on the design of modularized landing gears and evaluated our example design installed on a DJI F450 platform. For the experiments, we did not install an onboard camera for the UAV to detect perching locations or other sensors to navigate it in the environment. Instead, we 3D-scanned the laboratory environment beforehand and saved a point cloud of the environment. For perching location detection, we implemented a hybrid system based on the PCL (Point Cloud Library) (*56*) to detect feasible perching and resting locations. Concretely, as shown in Fig. 7, the system takes the environment point cloud as the input and first needs to decide whether a perching location or a resting location is desired. In practice, we always tried to find perching locations first and then looked for resting locations if the former was not available.

If some perching structures are desired, in addition to the environment point cloud, the system was provided with a set of shape primitives that were preferable for perching actions. In our examples, we showed perching by grasping on a stick and perching by hooking on a thin board. To detect such locations in a point cloud, we used the Random Sample Consensus (RANSAC) algorithm based on parameterized shape templates, and the results are shown in Fig. 2. For detecting resting locations, given that those actions rely on the customized contact modules, the detection is also based on the shapes of contact modules. As depicted in Fig. 7, the fast point feature histograms (FPFHs) were extracted from both the environment point cloud and the contact modules. Thereafter, we tried to register the contact modules to feasible locations in the environment and optimized the results using the iterative closest point (ICP) algorithm.

Once a perching or resting location was found, it needed to be verified by two additional steps. Because the UAV always approached those locations from top-down in an upright pose, we checked whether the surrounding area was collision free and whether the area allowed top-down approaching motions. As a negative example, for resting on an edge, the UAV could not stabilize itself by making contacts on the side edges of a box or a building; the edge had to be on top and approximately horizontal. Once a perching or resting location was confirmed, the coordinates of it were transformed to the VICON system, and the UAV navigated to apply the action.

Perching and resting control

To execute the actions for perching and resting, we applied a flight controller that mixed the position control and the attitude control of the UAV in a cascaded manner. The details of the controller design are provided in appendix S1. For perching actions, the UAV first navigated to the desired location; once the grasping or hooking actions were applied, the UAV turned off all rotors and stayed in the perching mode. If the UAV needed to turn over, we applied a proportional angular velocity controller to realize a smooth motion.

For resting actions, the UAV also needed to first navigate to the desired location. However, differently from the perching actions, the UAV only turned off or slowed down some of the rotors. In cases when one side of the UAV could totally rest on some structures, such as edge resting, the rotors at the corresponding side were turned off, and the rest of the rotors could still work to support the weight. In another case when the UAV could not totally rest on any side, such as the stand-resting, the UAV could slow down the rotors but still needed some lift to keep the balance.

In both of the above cases, we aimed at minimizing the power consumption to stabilize the UAV at the desired pose. This was achieved through the cascaded controller using a shifted reference point. Concretely, denoted by $\mathbf{p} \in \mathbb{R}^3$, the location of the UAV at the resting location, if we command the UAV to stay at $\mathbf{p}$, the rotors will still work at full speed to realize the precise pose control. To automatically slow down the rotors while keeping the UAV at the desired resting pose to stabilize contacts, we introduced a shifting factor $\Delta_r \in \mathbb{R}^3$ to shift the reference point toward the direction from which the UAV will obtain the resting support. Once the UAV has reached the resting location $\mathbf{p}$, the reference point for the controller will be shifted to $\mathbf{p} - \Delta_r$, and the rotors at the supported side will be stopped. Because of the physical contacts, the UAV in practice was not able to achieve the shifted reference. However, it slowed down the rotors to try to approach $\mathbf{p} - \Delta_r$ while keeping the pose upright. Additionally, as the UAV tries to approach the shifted reference point, it will actively exert force at the contacts; this effect can further improve the stability of resting actions.

Contact module design

The contact modules were used to passively stabilize the contacts between the landing gear and the resting locations. Therefore, we aimed at generating contact modules with shapes that could maximally resemble the typical contact geometries available in the environment. To keep the design general enough to accommodate as many scenarios as possible, we adopted the fingertip design algorithm from (*51*).

Concretely, the contact module design was formulated as an optimization problem addressed in three steps. First, given a working environment of the UAV, we provided the algorithm with a set of example shape primitives, which were representatives for describing typical shape geometries in the working environment. Thereafter, as shown in Fig. 8, by specifying a set of example contact poses, the algorithm extracted a set of contact areas that could be potentially used for resting contacts in the environment and represented them as point clouds. Second, the algorithm automatically determined the number of clusters and then clustered the extracted contact areas into different groups in terms of the geometric similarities between them. Last, modeled by a parameterized 3D surface for each contact module, the algorithm optimized the module's surface shape by minimizing the differences between the surface and all the contact areas in the corresponding cluster. Hence, the optimized contact module's surface maximally resembled the geometric features of the potential contacts and improved the stability of contacts for the UAV to rest at the corresponding locations. For a more detailed explanation of this algorithm, we refer the readers to (*51*).

In this procedure, the more example contact areas that were provided to the algorithm, the more potential clusters of contact areas were produced, and so the number of designed contact modules. This enabled the UAVs to rest at a variety of different locations, because the contact modules could be exchanged when working in different environments. Additionally, although the designs are maximally resembling the geometric features of contact areas, there were always differences between the designed contact module and the real contact locations in the environment. To minimize the effects given by this difference, we suggest fabricating the contact modules using soft materials so that some small differences at contacts can be compensated to improve the stability of contacts.

SUPPLEMENTARY MATERIALS

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Appendix S1. Flight controller design.
Table S1. Weights of parts.
Movie S1. Perching and resting actions test.
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Perching and resting—A paradigm for UAV maneuvering with modularized landing gears

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