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# A Powerline Inspection UAV Equipped with Dexterous, Lockable Gripping Mechanisms for Autonomous Perching and Contact Rolling

Angus Lynch, Corey Duguid, Joao Buzzatto, and Minas Liarokapis

*Abstract*— **Inspection of powerlines is a hard problem that requires humans to operate in remote locations and dangerous conditions. This paper proposes a quadcopter unmanned aerial vehicle (UAV) equipped with rolling-capable perching mechanisms and a depth-vision system for the purpose of autonomous power line inspection. The perching mechanism grips onto the power line, allowing the UAV to withstand external forces such as wind disturbances. Once engaged and applying the desired gripping force, the perching mechanism requires no power through the use of a ratcheting serial elastic transmission, allowing the UAV to perch indefinitely. The depth-vision system automates the perching and unperching procedures by estimating the position and pose of the UAV relative to the powerline. These measurements are sent to a local position controller that guides the UAV to and from the power line. Once perched, rollers in the fingers of the perching mechanism drive the UAV along the powerline, providing a close-up platform for inspection equipment. The proposed system was tested in an outdoor testing environment and shown to autonomously perch and unperch from a steel cable. The grippers force application was analysed and the UAVs powerless robust perch is demonstrated by total disconnect of power while perched. These results suggest that such a system could be a valuable tool for the upkeep of electricity networks.**

## I. INTRODUCTION

The regular inspection of infrastructure is a critical component in the maintenance of electrical grids. Detecting faults early can avoid or mitigate significant costs, damages, and outages. In the case of New Zealand, significant costs and time overheads of personnel are associated with inspection of powerlines, as helicopters are used to visually inspect much of the 12,000 kilometres of high-voltage transmission lines and 40,000 pylons [1]. Although this is an effective process, helicopters are expensive to operate and can result in significant damage and loss of life in the event of a failure.

Over recent years there has been an increase in the use of unmanned aerial vehicles (UAVs) for power line inspection, improving safety and cost by reducing climbing time [2]. These UAVs are typically driven to a pylon by an operator and flown up and around the tower and along the conductor to spot defects with onboard cameras and other sensors such as thermal imagery. However, the relatively short range and flight time of standard UAVs limit them from carrying out the kinds of cross-country inspections currently conducted via helicopter.

Fig. 1: The proposed perching and rolling capable UAV attached to a power line through its ratcheting, serial elastic parallel jaw grippers.

This paper proposes a solution that greatly extends the range and mission time of power line inspection UAVs. The proposed system utilises the conductors of power lines as highways to perch upon and roll along, providing an up-close platform for sensing equipment to inspect the lines. To travel past pylons and obstacles on the conductor the proposed grasping capable UAV system can unperch, act as a standard UAV to fly past the obstacle, and then reattach to the conductor. If combined with the means to recharge from the field – for example through inductive charging from the power lines – such a system could permanently inhabit the powerlines and constantly travel back and forth along extensive stretches of powerlines, from city to city across the electricity network. Ultimately, a UAV operating in this manner could present a safer, cheaper, and more environmentally friendly alternative to current modes of powerline inspection. To summarise, the contributions are:

- The design of a ratcheting serial elastic perching mechanism for the UAV consisting of two parallel-jaw gripping modules, capable of maintaining a gripping force without drawing any current while still preserving the ability to adjust gripping force during operation.
- The development of a high-speed regression-based algorithm for estimating, from depth maps, the local position and pose of a UAV relative to a power line.
- The experimental demonstration of reliable autonomous perching and unperching of the platform.

Please note that this work does not consider the influence of the electromagnetic field of a live powerline on a UAV physically interacting with it, but efforts have been made to position all electronics away from the line to make shielding more efficient.

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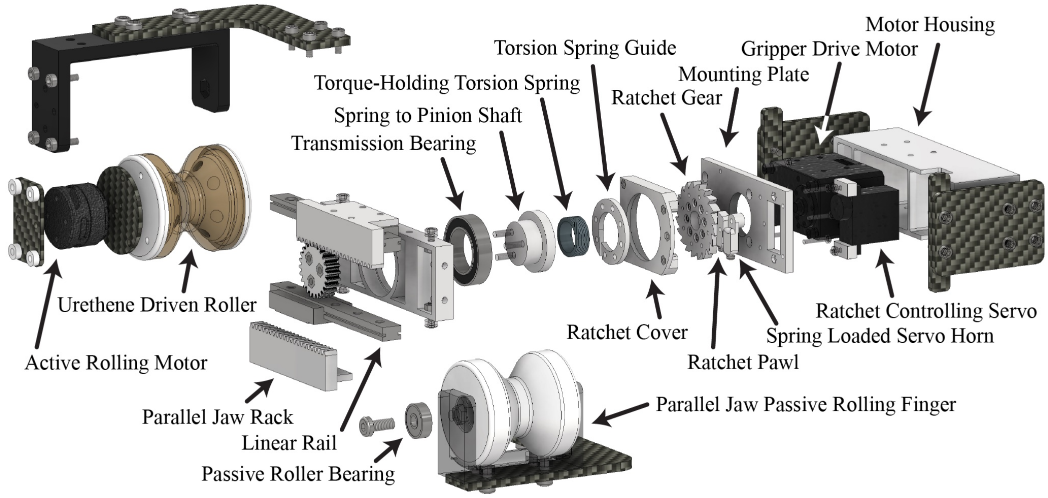

Fig. 2: Exploded view of the gripper module with a driven roller. The ratchet mechanism takes all load off the gripper drive motor to minimise power draw. The driven roller is used to travel along the power line.

## II. RELATED WORK

UAV Perching is when the aerial robot's weight is supported on a structure using grasping, attaching, or embedding solutions [3]. Various mechanisms over the years have been proposed to achieve this, and they are normally integrated with some sort of localisation method to facilitate the precise execution of the positioning required to achieve the perch. In [4], the UAV is designed to perch on top of thin, vertical boards such as road signs or billboards. In [5], a mechanism to perch onto circular posts is proposed, as well as a computer vision algorithm to facilitate perching. In [6], a UAV platform is bio-inspired from a sloth, where there are two perching points of contact on a bar, and the UAV is able to travel along the bar by climbing.

The works of [7]–[12] describe various perching mechanisms specifically designed to perch upon a power line. In [7], [9], [11], the UAV remains perched by passively resting on the line, and is able to drive along the line. The work in this paper takes inspiration from these papers, as the proposed perching mechanism is able to drive along the line once perched, but is also able to control the force the mechanism applies to the line, as well as maintain this force indefinitely without using any electrical power.

The works of [8], [13]–[18] describe various combinations of computation hardware, sensors, and algorithms to achieve the tracking of a powerline for the purpose of localising a UAV about the powerline. Some use offboard computation, and some use onboard computers like the Raspberry pi, or a Nvidia Jetson. In [15], a comprehensive review of sensors are tested for the purpose of powerline localisation, and shows the Intel Realsense D435i is capable of outdoor localisation of powerlines. Thi is also the camera sensor that we have selected for this work. In [8], the localisation method is also demonstrated to be capable of navigating a UAV close enough to the powerline for a perch maneuver to be achieved. In this paper we propose a new approach to detect a powerline at a high speed only using depth data.

## III. DESIGNS AND METHODS

This section discusses the designs of the test UAV platform and the perching mechanisms as well as the implementation details of the line localisation method.

### A. *Perching Mechanism*

The perching mechanism is the key mechanical component in this research. It is where the UAV makes contact with the powerline, and subsequently it is responsible for how the UAV perches and interacts with the powerline, as in Fig. 1. The grippers used in the perching mechanism are capable applying a constant grip force without drawing any power from the battery, enabling the UAV to perch indefinitely. While gripped they are also able to dynamically control gripping force and move along the powerline.

The approach taken in this work uses two parallel jaw grippers adapted with active rotating rollers acting as the dexterous tips of the fingers. Fig. 2 depicts the exploded view of all the components of the gripper while Fig. 3 shows the actual prototype. The parallel jaw gripper works with a single motor actuating a symmetric rack and pinion system that accommodates the two opposing fingers. The racks are mounted on carriers that slide on linear rails. Each rack carries a finger of the parallel jaw gripper. A transmission sits between the drive motor and the rack and pinion, which includes a servo controllable ratchet mechanism, and a serial elastic component. While there is no resistance at the finger tips, the pinion rotates synchronously with the drive motor input, driving the racks and thus the fingers. After the fingers have made contact with the powerline, and therefore stop moving, the servo motor continues to rotate and store energy in the serial elastic component. Once the desired torque in the serial elastic component has been reached and the ratchet is engaged, the drive motor can switch off, allowing the entire mechanism to not draw any current. Now that the ratchet is engaged the serial elastic component continues to apply force to the fingers of the gripper indefinitely. Once required, the

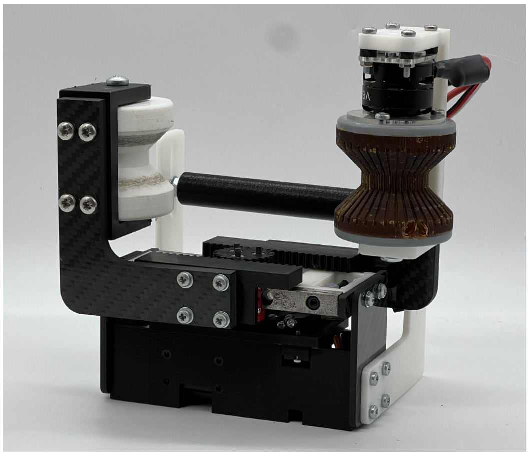

Fig. 3: Prototype of the active rolling gripper module used for perching.

gripper drive motor can be powered back on, and it applies an increased force. This increased force takes all load off of the ratchet system and allows it to smoothly disengage, enabling the motor to drive in reverse to unwind the serial elastic component, and subsequently open the grippeing mechanism. The physical layout of the proposed series elastic system can be seen in Fig. 2.

For the examined application, once the powerline is within the gripper mechanism, the powerline is trapped geometrically yielding a secure and robust perch. The gripper is also capable of driving one of the rollers at its finger tips with another motor. A hybrid deposition urethane roller was used to increase the friction between the driving roller and the metal powerline. With this design, the UAV can drive back and forth along powerlines without engaging its propellers. This capability is bolstered by the ability to dynamically control the stored grip force applied to the powerlines, allowing the UAV to climb steeper inclines by tightening its grip. The gripper modules are driven using Dynamixel XM430-350R servo motors, and the ratcheting mechanism is actuated by an MN90 180° servo motor. The motors in the gripper modules are controlled using an ATMEGA644p microcontroller. The microcontroller controls the gripper modules using a Finite State Machine (FSM). The gripper can swap between closing and opening without engaging the ratchet to quickly grap and release, but then when commanded to, it engages the ratchet and drives to the target inputted torque, and switches to an idle state as to not draw any current. From this ’clamped’ state, the FSM ensures that it follows the correct unclamping sequence to not damage the ratchet or motors. This system ensures that the operation is smooth and asynchronous with the flight control.

### B. Relative Localisation from Powerline

The proposed powerline inspection UAV platform is equipped with an upwards-facing stereoscopic depth camera system (Intel Realsense D435i) that allows it to provide relative position data. From this data the UAV can retrieve the yaw, vertical, and perpendicular offsets relative to the powerline. The algorithm to detect this line is intended to be both lightweight on the microprocessor, as well as deterministic, therefore no forms of machine learning models are used. Furthermore it always takes the same amount of computational time to run independently of the resolution of the frame, so the rate that it runs is consistent and predictable.

TABLE I: Table of characteristics of the proposed grasping and perching capable, powerline inspection UAV.

| Characteristic | Value |
|---|---|
| UAV takeoff mass | 4.84 kg |
| Maximum takeoff mass (UAV+payload, 85% thrust, calculated from motor & propeller data sheets) | 11.1 kg |
| Flight Time (50% thrust, calculated from battery capacity) | 15 Minutes |
| Rolling Time (Drawing 500 mA, calculated from battery capacity) | 12 Hours |
| Rolling Speed (On horizontal wire, calculated from roller radius and motor maximum RPM) | 9.71 m/s |
| Gripping Force Per Module (Measured in experiments section) | 42 N |

To detect the line, we start by capturing the depth frame from the Intel RealSense and clipping its depth values to be within the working range of the task, as well as filling ’depth shadows’ that occur around near objects with the maximum working distance so as to clean the data. We then compute the gradient between depth values moving from left to right across the frame. We assume that a large minimum is on the leading edge of the line, and a large maximum on the trialing edge. Using this assumption we find the center value between the minimum and maximum values. We then run linear regression where x is the row value, and y is the center value along that row. This produces a statistical estimation of where the line may be, as well as an estimation if there is a line in the frame at all. False positives are mitigated by checking the standard error of the linear regression. If a line is detected, the local position relative to the powerline is measured. Fig. 5 show the estimated line on actual data from the RealSense camera, demonstrating resilience to noise and background objects in sight.

The yaw is calculated from the gradient of the linear regression, vertical position is taken from the depth data where the line is present, and the perpendicular position is calculated with the equation of the line and the measured depth. The estimations are then used to correct GPS values to be centimeter accurate when operating around the powerline, which produces the capability to both perch and unperch.

### C. The UAV Platform

The backbone of the system relies on a quadcopter UAV platform that has been developed to accommodate the proposed grasping and perching capable mechanisms by combining off-the-shelf motors, propellers, batteries, power, and control electronics with a lightweight frame based on carbon fibre tubes, and 3D printed connecting components. Some key parameters about the UAV platform are provided

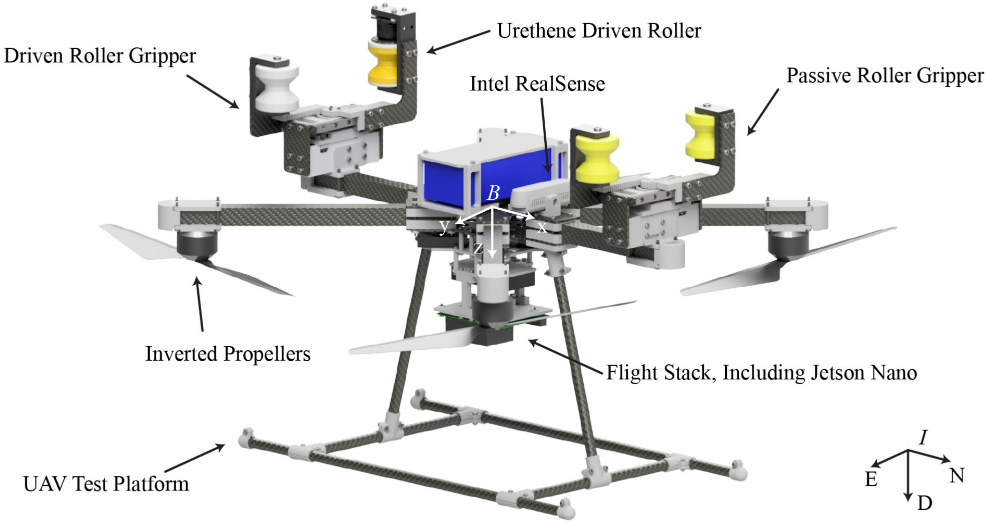

Fig. 4: Schematic of UAV combined with the perching mechanisms. The coordinate system of the UAV is shown fixed to the body of the UAV, and the world frame is shown in the North, East, Down annotation. Inverted flight system is used to allow a large area on the top side for the perching mechanism to reside. The location of the line detection camera is also depicted.

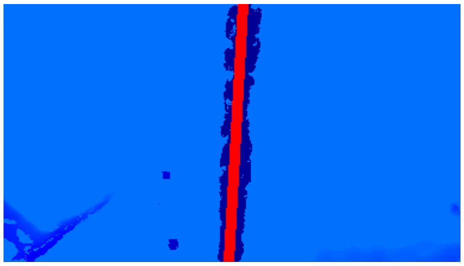

Fig. 5: Depth map with predicted powerline position, shown in red. Depth data is captured with an Intel RealSense D435i, and processed by a python script running on an onboard Nvidia Jetson Nano companion computer. Noise rejection is exhibited.

in I. The UAV uses MN4014 400kv BLDC motors, combined with 16"x5.4" propellers for its propulsion system. The propellers were chosen to be mounted in an inverted configuration so that the entire top face of the UAV is free for the perching mechanism to be installed.

A Pixhawk 4 running PX4 is used as the main flight controller processor, which is connected to a 2.4 GHz radio controller for manual operation and testing. Relative localisation estimates are found using depth data from the onboard Intel RealSense d435i camera and computed with a Nvidia Jetson Nano as a companion computer to the PX4. Communication between the PX4 and Jetson is conducted through a UART serial port, using MavLink messaging for off-board position set points. A M8N GPS module is used to acquire an accurate localisation of the platform during the execution of outdoor experiments.

## IV. EXPERIMENTAL RESULTS AND DISCUSSIONS

### A. *Autonomous Perching Experiments*

To experimentally validate the efficiency of the designs of the grasping and perching capable powerline inspection UAV proposed in this paper, outdoor flight experiments were conducted. To simulate an inactive power line perching target, an 8 m long, 24 mm diameter braided steel cable was suspended between 2 posts approximately 3 m from the ground in an outdoor environment in the island of Waiheke (Auckland, New Zealand).

Fig. 6 shows snapshots of the UAV executing the full test maneuver of perching, driving along the powerline, and unperching. Starting with step A, the UAV is commanded to approach a way point known to be within the visual range of the powerline. Then, in step B, the localisation system detects the powerline and begins to produce setpoints to the UAV where the estimated location of the powerline is offset from the estimated current location of the UAV. This causes the UAV to align with the wire in the Y and rotation around Z directions (Fig. 4 shows the local coordinate system of the UAV). After these axis are aligned, the localisation system commands the UAV to incline to come into contact with the wire, where it engages its grippers so as to perch. Shown in Fig. 6-C, the UAV platform has finished perching and is disarming its flight system preparing to drive on the powerline using its active rolling elements located at the fingertips of the gripping mechanisms. Shown in Fig. 6-D and Fig. 6-E, the UAV then demonstrates its ability to drive backward and forward along the powerline as desired. It can use this capability to travel the span of powerline between two power pylons, much more efficiently than flying, while having an up-close view of the line. However in this outdoor experiment there is not another powerline to perch to after the end of this span, so the UAV returns to the middle, and demonstrates unperching in Fig. 6-F.

Fig. 7 shows the flight log data of this experiment, where we plot the estimated Y position and altitude of the drone, straight from the flight controller. We also plot on the same axis the setpoint of each data point respectively. The setpoints are broken into 4 distinct sections:

1) in subfig. 7-A, the UAV has taken off and is loitering around the takeoff location awaiting instruction from the onboard computer,

Fig. 6: Instances of the autonomous perching and unperching experiments that have been conducted with the proposed grasping and perching capable powerline inspection UAV platform. The UAV approaches the powerline (A) and begins to track the line (B). It then autonomously perches (C), and is able to remain perched indefinitely. It can then translate along the powerline (D, E) and when applicable, autonomously unperch (F).

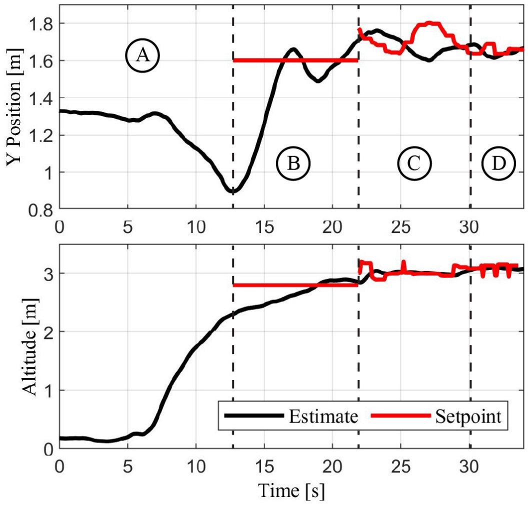

Fig. 7: Plot of flight data from outdoor experiment. In A, the UAV has taken off and loiters. In B, the UAV is commanded to go to a way point known to be within the visible range of the powerline. In C, the UAV is commanded to perch onto the wire, where the setpoint is a localisation corrected value. In D, the UAV has perched and the platform is powering off.

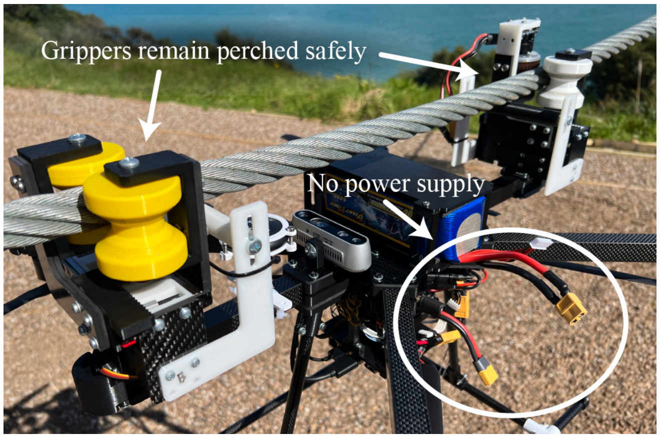

Fig. 8: The proposed perching and rolling capable UAV platform remains perched even during a complete loss of power. In this instance we have disconnected the battery to demonstrate this capability.

2) it is then commanded to travel to a waypoint which is known to be within visual range of the powerline as shown at in subfig. 7-B,
3) once the UAV has settled at this location, the localisation starts producing setpoints to the flight controller so as to align the platform with the powerline, as shown in subfig. 7-C,
4) once the UAV has aligned with the power line, the altitude setpoint is changed slightly to raise the UAV to contact the wire, just before the transition to D where the UAV has fully perched onto the powerline.

The results of this experiment demonstrate the ability of the proposed UAV system to perch onto a powerline in realistic settings. Fig. 7 shows that the system is robust to a degree of uncertainty, as we observe that the Y position does not converge onto the setpoint immediately, which is likely due to external disturbances such as light winds. However, the system is still capable of controlling the UAV in perching, as demonstrated in Fig. 6

### B. Complete Power Loss Experiment

Fig. 8 shows the perching mechanism in action, where the UAV is perched on a steel cable simulating a powerline. The battery is completely disconnected to demonstrate that the UAV requires no power to remain securely perched. This design could facilitate the UAV permanently inhabiting the powerline network, and taking advantage of a recharging solution such as deploying solar panels or inductively charging from the powerlines.

### C. Gripper Force Experiment

In order to collect data of the maximum force exertion that the grippers can achieve, a test rig was created to measure force and motor current in a laboratory environment. The grip force was measured and logged at 1 KHz by a BIOPAC MP36 data acquisition unit with the SS25LA

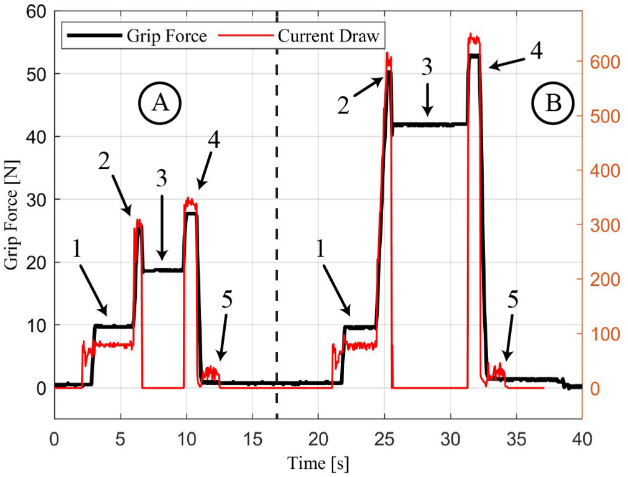

Fig. 9: Grip force and current draw of a single gripper module. In A, the gripper applies the force used for the flight experiments. In B, the gripper exerts maximum non-destructive force. 1 is initial contact with the wire, 2 is applying desired grip force, 3 is passive stored force, 4 motor reengages to release pressure from ratchet, 5 gripper opens. Force data was gathered with a BIOPAC MP36 data acquisition unit with the SS25LA hand dynamometer.

hand dynamometer. The current draw was gathered using the Dynamixel motors own internal current draw reporting, at 50 Hz. Fig. 9 shows the result of this experiment, where first the gripper was set to apply the same force as used in the flight experiments of this paper. Then the gripper demonstrates its maximum force output, applying 55 N of grip force at the peak, while being able to apply 42 N of force indefinitely while drawing 0 current (demonstrated in portion 3 of the curve). The two different grip forces display the versatility of this gripper, being able to control final grip force to more effectively manage friction with the wire while driving than simply relying on the force due to gravity. Using the same experimental setup, the true linear relationship between a current setpoint of the motor, and the actual force applied was derived. Twelve measurements were acquired, spaced 50 mA apart, and the resultant grip force on the sensor is found to be linear, where the force is equal to 86.6 N per amp of current, with an offset of 5.65 N to account for the non-linearites when the current is very low.

## V. CONCLUSIONS

This paper presented the design, prototyping, and experimental validation of a perching and rolling capable UAV for the autonomous inspection of powerlines. The design utilises ratcheting, series elastic, parallel jaw grippers equipped with active driven rollers to securely perch upon and travel along the conductors of powerlines. Depth-sensing based computer vision is used to estimate the local position of the UAV to facilitate autonomous perching and unperching. The UAV propellers can be used to avoid obstacles present along the conductor or travel past the pylons. The results presented in this paper demonstrate the following capabilities of the proposed UAV design: i) autonomous perching and unperching, ii) secure perching with no current draw, iii) and energy efficient travel along power lines. The proposed platform has a large excess of payload capacity, allowing for installation of sophisticated powerline inspection equipment. It is also large enough that it could facilitate integration of recharging methods such as deployable solar panels or an inductive power charging system.

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