Retraction

Retraction: Modeling and development of a fundamentally new way of landing a quadcopter on inclined surfaces (J. Phys.: Conf. Ser 2061 012109)

Published 23 December 2021

This article has been retracted by IOP Publishing following an allegation that this article substantially overlaps with [1]. IOP Publishing has investigated in line with the COPE guidelines, and agree that while the reference is listed in the article, the overlap is substantial and is unethical. Consequently, this paper has been retracted by IOP Publishing. Citations to this work should be redirected to [1]. The authors agree to this retraction.

[1]. John Bass and Alexis Lussier Desbiens, (2020), 'Improving Multirotor Landing Performance on Inclined Surfaces Using Reverse Thrust', IEEE Robotics and Automation Letters, Volume: 5, Issue: 4, https://ieeexplore.ieee.org/abstract/document/9143402

Retraction published: 23 December 2021
Modeling and development of a fundamentally new way of landing a quadcopter on inclined surfaces

F F Olenko, S O Malakhov
Admiral Ushakov Maritime State University, 93 Lenin Ave., Novorossiysk, 353924, Russian Federation
E-mail: 0feliks0@gmail.com

Abstract. Methods and software and hardware for modeling and developing a fundamentally new way of landing a quadrocopter on inclined surfaces are discussed in the paper. The current state of the project under elaboration is conditioned and described. Various approaches to the solution are feasible due to the complexity of the considered issue. Solutions can differ both in the distribution of control functions between the ground control station and the quadcopter itself, and in the choice of principles that can be used as the basis for the control system and determine its design and dynamic characteristics. Simulation and testing processes demonstrate that reverse thrust alone can increase the landing zone of an average mass quadcopter, almost doubling the maximum tilt angle at which a landing maneuver is made, thus, allowing for a high vertical speed landing. It is clearly shown that low-power adhesion mechanisms such as electrical adhesion, switchable magnets, grippers or dry glue are activated after landing, allowing it to stay on the surface after the back thrust has ceased. This can be useful in situations where sudden interference is likely to occur. Such a result is achieved using a classic quadrocopter as DJI F450 without adding any equipment.

1. Introduction
The application of unmanned aerial vehicles (UAV) for civilian purposes has dramatically increased in recent years as they become more affordable, versatile, and safer to fly. However, the vast majority of commercial multicopters has a limited landing area and is only recommended for landings on flat and horizontal surfaces. Sloping surfaces can cause UAV tipping due to the change in thrust direction and the UAV’s rigid suspension [1]. Besides, typical flight controllers are programmed to keep the engines on while even the smallest activity of internal UAV systems occurs, which can result in continuous downhill travel on small inclines.

New multicopters are equipped with vision sensors mounted on the bottom part of their hull, which in turn help them find suitable landing spots during automatic landing [3]. Increasing the landing range of multicopters can open up a wide range of possibilities for hardware and software enhancements by enhancing the number of possible landing zones or situations. For instance, UAV are able to land on sloped roofs in residential areas.

2. Problem statement
Aspects of modeling and development of a fundamentally new way of a quadrocopter landing on inclined surfaces using reverse thrust are discussed in the article [4]. Landing using reverse thrust does not force UAV developers to use quadcopters with a low center of gravity in projects, and,
accordingly, low weights, which facilitates maneuverability, but significantly reduces the carrying capacity, functionality, performance and quality of the equipment used on it. UAV landing ways by passive adhesion methods (micropips and dry adhesives), through the multi-rotor maneuverability to create highly dynamic landing maneuvers and sticking on inclined surfaces, as well as landing with small onboard lasers, cameras to measure the inclination of the landing site are a distinguishing feature from the landing using reverse thrust [1, 2]. Moreover, there is another significant disadvantage that the multicopter becomes more susceptible to weather interference during takeoff and landing, such as gusts of wind, rain or snow (Figure 1).

![Figure 1](image1.png)

**Figure 1.** Quadcopter landing during landing on a plane of 25°: (a) – quadcopter is tipped over; (b) – quadcopter does not land due to undefined bounce; (c) – successfully lands using reverse thrust.

A multicopter has several nodes for controlling movement in space, which, in turn, consist of an engine and a propeller. Each of these nodes rotates at different speeds, creating an axial force on the rotor axis and torque around the axis. These forces create a net thrust force and moments in the three main axes of the quadcopter. Then it becomes obvious that conventional multirotors are machines with insufficient drive: they have six degrees of freedom, but only four of them are involved. In addition, rotors' force cannot be “negative” (towards the copter footing) as the motor controllers (ESC) allow the rotors to revolve in only one direction.

The technology available on multirotor allows multicopters to land only on stable horizontal surfaces. Besides, they are not able to land on inclined surfaces, and this is partly due to the thrust redirection after the initial impact (mechanical limitation of the multicopters) and their flight controller preventing the rotary motors from shutting down until the copter stops moving (software limitation). Therefore, multirotors must perform a highly dynamic maneuver to land on an incline. The drone must tilt and direct the thrust vector towards the slope to get close to it, but it will crash into the slope in this orientation [1]. It must change the orientation creating a moment due to the differential thrust of the rotors, and align its thrust vector almost perpendicular to the slope in order to reduce the speed before impact. If contact is too abrupt, the drone will bounce back (Figure 2).

However, there is another method used by helicopter pilots when landing on inclined ground - safer but slower as well. Cyclic control is used to make a force on the rotor, thereby creating a tilt of the rotor when one of the helicopter’s landing gear touches the ground and the helicopter lands on an inclined surface (Figure 3). The pilot can place the other end of his landing gear firmly on the ground while slowly reducing the distance. Nevertheless, the method allows landing only on slightly inclined surfaces, for example, at an angle of 10° which makes it extremely ineffective when operating the multicopter in extreme conditions [8].
Figure 2. An example of a dynamic maneuver that allows multicopters to land on an inclined surface.

Figure 3. Landing a helicopter on an inclined surface.

Based on this, the best solution is to use the new multicopter landing technology using reverse thrust. This technology makes the approach to inclined surface faster and the copter less susceptible to ambient noise [1, 3]. Reverse thrust is used to reduce the impact force, as well as increase the efficiency of friction, to dissipate the driving energy when the hardware system lands on an inclined surface. Besides, the angular movement significantly decreases due to bounces, which allows shortening the duration and required distance when landing [1, 4]. The use of reverse thrust does not require any revolutionary hardware or software modifications to the multicopter. Due to this, and its high versatility and practicality, the development and implementation of the technology is an extremely urgent task in the field of unmanned aerial vehicles, which contributes to its realization in the next few years.

A drone model of the DJI F450 type with specialized landing legs installed on it, instead of ordinary ones, on a torsion spring, which allow the copter to more effectively damp the impact on the surface during landing, as well as reduce the braking area, was used to develop a fundamentally new method of landing a multicopter by means of reverse thrust. We used several types of mathematical models at once in such environments as Matlab 2016b and Autodesk AutoCAD 2020 to create an accurate digital prototype of a multicopter with a reverse thrust landing technology through a detailed description of all its segments [6, 9].

3. Materials and methods
A dynamic model for simulating a quadcopter landing on several inclined surfaces with various tilt angles, as well as several landing strategies was developed by the first mathematical model, it is also a game model. Assuming that the quadcopter is well oriented on the surface before the landing maneuver, then its motion can be viewed in a two-dimensional plane (tilt and yaw do not exceed 10°), which simplifies the model by reducing the number of motion equations and the number of contact calculations. The multi-body model is applied to simulate the behavior of a quadcopter's torsion landing gear, which flex under landing loads (Figure 4). In turn, the model consists of three rigid
bodies: one quadcopter and two landing legs. The appliance of 2D models also compensates for the angular momentum of the rotors greatly simplifying the task [5].

![Diagram of a simplified model of a quadcopter and landing gear, a frame of reference and forces acting on a dynamic model, unit vectors oriented in the XZ plane](image)

Figure 4. Diagram of a simplified model of a quadcopter and landing gear, a frame of reference and forces acting on a dynamic model, unit vectors oriented in the XZ plane.

Further, the descriptive model was used in conjunction with the game model to simulate two methods of reverse thrust landing and choose between the best one. The classic method involves turning off all of its engines by the autopilot when its inertial measurement unit (IMU) detects an impact [4]. Another method was to apply maximum back thrust to all motors at the moment of impact, which increases friction and decreases the amplitude of the bounces, helping the quadcopter stop quickly.

These two landing methods were tested with simulations in a range of tilt angles (from 0° to 45°) and vertical impact velocities (from 0 to 2 m/s) on surfaces with various types of friction. The simulation was conducted five times using five best sets of parameter for the copter when landing on inclined surfaces with low and high friction [5].

Based on the simulation outcomes, it was revealed and proven that the appliance of reverse thrust in the landing algorithm provides significant advantages over other mechanical copter improvements by gradually increasing the maximum slope of the copter landing. It was designated that the control of the maximum reverse thrust force during landing several times more successfully fulfills the task in contrast to the classical reverse thrust method. The maximum reverse thrust control also ensures quicker landings over a wider tilt range. However, if the inclination angle of the landing surface is close to the maximum, landing on a surface with high friction will be complicated. On this type of surface, the quadcopter is exposed to short contacts but with frequent sequencing, instead of longer sliding contacts resulting in less frictional energy dissipation. The average time to land and come to a complete stop for the copter hardware system is twice as long for a high friction surface as for a low one. The probability of the multicopter flipping enhances with high speed and force of the copter hitting the surface during a high friction landing.

4. Results and discussion

Figures 5 and 6 show the black dashed line indicating the natural hardware limits of the quadcopter when landing with and without reverse thrust. In fact, the quadcopter glides from the rest state only if the surface tilt exceeds 22° on a surface with a low friction coefficient. The limit on a surface with a high surface friction is the surface tilt at which the quadcopter is toppled from rest state (35°), which occurs before sliding. With reverse thrust, these limits increase up to 48° and 67°, respectively, but
these indicators are not the limit for this technology. Improvement measures of the ability to land on an inclined surface will be applied in further research. Moreover, low-power adhesion mechanisms such as electro-adhesion, switchable magnets, grippers or dry glue can be activated after landing, and it allows staying on the surface after the reverse thrust cessation [8].

More than two hundred and forty test landings using reverse thrust, as well as forces potentially affecting the mathematical prototype of the UAV DJI F450 software and hardware complex were calculated and modeled in the MATLAB 2016b mathematical modeling program. The DJI F450 quadcopter was controlled by an Arduino Uno microcontroller, an expansion board for connecting Arduino peripheral modules Adafruit Servo Shield, using a Sparkfun Razor IMU board (data collection at a frequency of 1 kHz and filtering with a low-pass filter and gyroscope, accelerometer and magnetometer systems integrated into it) and the Xbee S1 digital radio communication for data transmission. The Arduino microcontroller was programmed for a simple behavior in space during landing, the main modulation condition was the need to avoid unnecessary deviations in space as much as possible when landing.

![Figure 5](image1.png)

**Figure 5.** Demonstration of landing a multicopter with and without reverse thrust on a surface with a high friction coefficient: (a) – with reverse thrust; (b) – without reverse thrust.

![Figure 6](image2.png)

**Figure 6.** Demonstration of landing a multicopter with and without reverse thrust on a surface with a low friction coefficient: (a) – with reverse thrust; (b) – without reverse thrust.

The Arduino Uno activates the reverse thrust method of the quadcopter landing on the first collision at a threshold of 2g measured by the accelerometer. The impact speed was recorded using a motion capture system. Successful and failed landings were added to the quadcopter landing maps. Declines were maintained at speeds below 1.2 m / s, since the likelihood of breakage of the plastic landing gears is feasible at higher impact speeds.

The experimental outcomes confirm the simulated characteristics of the hardware and software system, as well as the accuracy of the dynamic model at landing time. Besides, the F450 commits rolls
and yaw on average around 19° and 27°, respectively, after the initial impact. This demonstrates that the copter model is relevant even for predicting the landing range with significant deviations from the given 2-dimensional conditions.

The green area represents successful landings within 45 cm of the first collision on simulated landing maps using the surface reverse thrust with the low and high friction coefficient in Figure 5, while the orange area indicates possible conditions for a successful landing within 1 meter. The gray area means the quadcopter flies within 1 meter of the collision place. The white area designates the quadcopter flip in the course of the landing maneuver. Figures showing the distance and time required to simulate the F450 up to the complete UAV stop, are located to the right of the maps. The black dashed line represents the friction limit for a low coefficient surface while the “titling” limit indicates a high coefficient surface [8].

The angular velocity of the quadcopter increases after hitting the rear leg until the front leg touches the ground. The high angular velocity on the second impact causes the quadcopter to either keep bouncing or topple over. This phenomenon is emphasized by the high rigidity of the quadcopter landing gear and low damping. An angular impulse can be generated to eliminate the angular velocity before the second impact by the reverse thrust. Simple predictive modeling can determine the delay and duration of this angular momentum required to eliminate the angular velocity of the quadcopter and land parallel to the surface at the second impact, using data on the surface tilt and predicted impact velocity. Since the pulse requires precise timing, the power of the brushless motors is reduced to 10% on impact, and then, at the right time, a pulse is generated by sending a signal through the Arduino Uno microcontroller increasing the power of the front motors to 80%. This strategy avoids reversal delays. Both rotors are commanded to generate maximum reverse thrust to facilitate surface traction after the impulse is complete.

This approach was tested in the MATLAB Simulink Version 8.8 (R2016b) simulation environment with the same vertical impact velocity and slope tilts ranges as previous simulations on both types of surfaces. Several combinations of impulse delay (time between impact and onset of impulse) and duration - from 0 to 260 ms and from 0 to 160 ms, respectively, for each combination of speed and tilt angle were simulated to find the optimal software and hardware UAV configuration. The combination of impulses minimizing the angular velocity at the moment of the second impact was chosen. This procedure was repeated for each of the five best F450 parameter sets for each surface type. The obtained average simulation values are presented on the landing map in Figure 7.

![Figure 7](image-url)

**Figure 7.** Simulated landing maps of two types of landing surfaces using impulse control: (a) – low friction coefficient; (b) – high friction coefficient.

This method slightly increases the maximum tilt at which the quadcopter can land within 1 meter over a wider range of landing speeds. Risks are significantly reduced as tilting occurs less frequently [6]. In addition, the reverse thrust application is required to enhance landing accuracy as shown by the black dashed line in Figure 6. However, it should be noted that only the impulse control of the reverse
thrust is compatible with the basic control of landing on a horizontal surface in terms of landing on an inclined surface [3]. This can be explained by the creation of a linear impulse in the simulation environment, which pushes the drone off the slope.

As a result, the faster reverse thrust expanded the landing zone significantly more than the impulse with conventional engines, and also narrowed the failure zone. Landing times also decreased, especially for high-friction surfaces, demonstrating that enhancement of the engine-reversing technology can significantly contribute to improved multicopter landing. Faster motor reversal is realized with encoder motors or variable pitch rotors.

5. Conclusion
It should be noted that the development and modeling of a fundamentally new technology for landing multicopters on inclined surfaces using reverse thrust together with the use of bi-directional engine technology was described in the paper. Through simulation and testing, reverse thrust alone can increase the landing area of a small quadcopter, almost doubling the maximum tilt angle at which it can land, allowing for a high vertical speed landing. This can be useful in situations where sudden interference is likely to occur (for example, landing on a roof in windy conditions). The result was achieved using a classic quadcopter of the DJI F450 type without adding any equipment.

The use of angular impulse after the initial impact aided landing maneuver by eliminating unwanted subsequent bounces. Moreover, a faster change in thrust significantly increased landing accuracy. Further development will include testing of the proposed solutions on a physical model. Using the developed model in the scientific work, its parameters will be adjusted to determine the stiffness and damping of an ideal landing gear to minimize bouncing and tilting. The proposed method can be applied to landings on moving surfaces such as the boat deck or high-speed vehicle.

References
[1] Bass J, Desbiens A L 2020 Improving Multicopter Landing Performance on Inclined Surfaces Using Reverse Thrust. IEEE Robotics and Automation Letters 5 5850 – 5857
[2] Kooi J E, Babuska B 2021 Inclined Quadrotor Landing using Deep Reinforcement Learning arXiv:2103.09043, available at https://arxiv.org/abs/2103.09043
[3] Mehanovic D, Bass J, Courteau T 2017 Autonomous Thrust-Assisted Perching of a Fixed-Wing UAV on Vertical Surfaces Lecture Notes in Computer Science book series 10384 (LNCS).
[4] Thomas J 2016 Aggressive flight with quadrotors for perching on inclined surfaces J. Mech. Robot. 8(5), 051007
[5] Kalantari A 2015 Autonomous perching and take-off on vertical walls for a quadrotor micro air vehicle. In IEEE International Conference on Robotics and Automation (ICRA), pp. 4669-4674, doi: 10.1109/ICRA.2015.7159846
[6] Kumar I A, Indragandhi V, Maheswari U Y MATLAB®/Simulink 2020. Software Tools for the Simulation of Electrical Systems (PSG College of Technology)
[7] Daler L 2013 A perching mechanism for flying robots using a fibre-based adhesive. International Conference on Robotics and Automation, May 6-10, Karlsruhe, Germany.
[8] Graule M 2016 Perching and takeoff of a robotic insect on overhangs using switchable electrostatic adhesion Science 352 978–982
[9] Kondratiev A, Boran-Keshishyan A L, Popov A N 2016 Model course to revalidate deck officers’ competences using simulators WMU Journal of Maritime Affairs 15 163-185