Mechatronic design of a wall-climbing drone for the inspection of structures and infrastructure

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Abstract. The inspection of structures and infrastructure is nowadays a relevant problem in Europe, and especially in Italy, after the recent collapses of bridges. Large research activity has been therefore devoted towards the inspection for further management and maintenance of large infrastructure. For many sites such as large structures difficult to access mobile robots, mainly UAVs, hybrid mobile robots, and climbing robots may represent an efficient solution, offering an excellent platform to carry devices and sensors. Beside these great advantages there are some limitations, among all the security distance to maintain during the flight operation, avoiding the robot to get too close or attached to the surface to inspect. In addition, when dealing with structures exposed to harsh environmental conditions such as strong winds, the risk of collision and damage of the robot is quite high. In order to overcome those limitation related to vertical surfaces, large infrastructures and outdoor inspection, wall climbing drones have been developed in the very recent years being able to fly and climb a vertical surface, In this paper, we present the mechatronic design and simulation of a wall-climbing drone based on a multirotor with legs equipped by passive wheels.

Keywords: Robotics, Mechatronics, Wall-Climbing Drone, Inspection and Monitoring.

1 Introduction

The integrity of infrastructure and structures, such as bridges, skyscrapers, wind turbines and large aircraft, is closely related to safety issues. Nowadays, due to their aging and potential concerns about their damage or even their collapse, the interest in Structural Health Monitoring (SHM) has increased worldwide, [1,2]. Although there is a great deal of research on inspecting large structures difficult to access using Unmanned Aerial Vehicles (UAVs) or mobile robotics [3-9], in most of cases the inspection still require great human efforts, the installation of additional infrastructure or use magnet-based technology or vacuum adhesion, and it is time consuming and high-cost. In addition, in most of cases, it requires the stop of the traffic causing big problems to the viability. The new trend in robotics inspections made by UAVs addresses the development of a new concept of a wall-climbing drone, which allows approaching to any type of structure by flying and adhering to the target using a perching mechanism. Furthermore, it does not require the installation of any additional infrastructure and which offers maximum mobility and safety such as the robot to wall. These robots have greater mobility than existing wall robots because they can fly. Since the robot can also adhere to the surface, it can perform a close inspection and maintenance of the structure [10].

An example is the SCAMP (Stanford Climbing and Aerial Maneuvering Platform) project [11], which is able to fly, passively perch, climb, and take off. Small drones are generally perfect for resisting to small impacts such as collisions with a wall, they are extremely quick in movements and changes in direction, and can reach higher adhesive forces than larger drones. SCAMP is able to fly, climb, immediately recover stability in the event of a fall and slip into those tunnels where other larger drones cannot access. For its construction, carbon fiber materials were used, drawbacks are related to small dimension (and duration) of the battery. Another example is the VOLIRO [12], which is a novel aerial platform that combines the advantages of existing multi-rotor systems with the agility of omnidirectional controllable platforms. It consists of a hexa-copter with tiltable rotors allowing the system to decouple the control of position and orientation. Nowadays, multirotor drones have reached a high level of popularity. Although drones with four or six rotors are common and particularly fast, they are not known for their flexibility due to their fixed rotors [13]. The novelty of VOLIRO is the use of six rotors that operate independently and can rotate 360 degrees achieving interesting features, such as flying on the side, flying upside down and in an upright position.

Having in mind the above-mentioned technical solutions, in this paper, we present the mechanical design and first prototype of a wall-climbing drone to be used for inspections.

2 Mechanical design of the wall-climbing drone

The wall-climbing drone should possess the following characteristics: it must fly and move over a vertical surface by keeping the contact at a given distance; it must carry sensors, e.g. a camera; it should be low-cost and easy operation. The wall-climbing drone is designed for indoor and outdoor applications. Wall-climbing systems that can be used are wall-sticking mechanism, tilt-rotor-based drones, or multi oriented rotors, as it was recalled in the previous section.

In this context, we have developed a drone with four fixed rotors (quadrotor) for flying mode and modify the initial design adding two rotors with fixed axes mounted orthogonally with respect to the first four. In order to be able to get close to a wall keeping a fixed distance, two limbs are used with wheels at the end tips. The additional two rotors give suitable propulsion to adhere to the vertical wall, the wheels at the leg tips allow to climb with low friction. The proposed solution is shown in Figure 1.

The two legs are equipped with lightweight wheels for maintaining the contact with any vertical surface. Suitable springs allow damping and mitigate the contact with the vertical surface. The spring design is shown in Figure 2. Main characteristics of the springs are K=0.5 N/mm; C = 0.01 N/(mm/s); L = 32.34 mm; L_0 (F=0) = 30mm. The legs' maximum span range is 60-140 deg. Mechanical specifications are reported in Table 1.

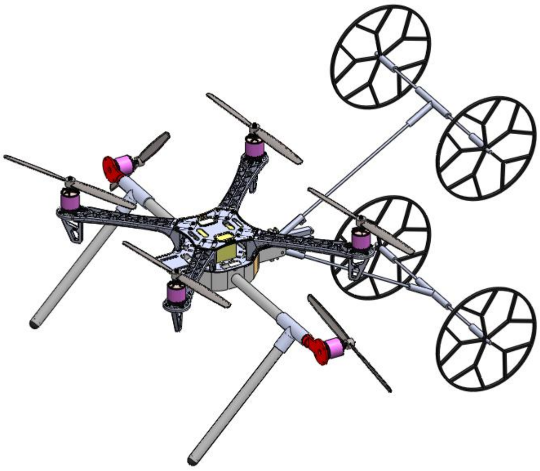
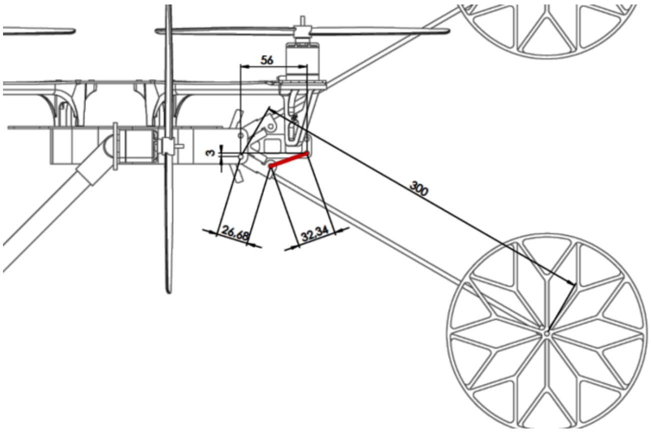
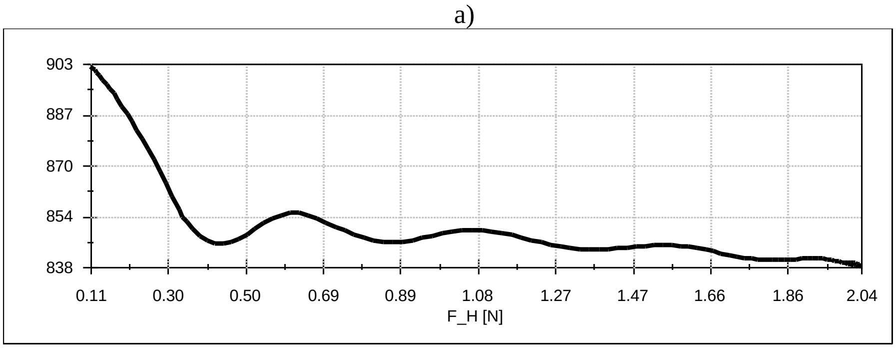


Fig. 1: Mechanical design solution for the proposed wall-climbing drone.



a)



b)

Fig.2: Design of the spring a); b) distance from the wall D_w VS propulsion force F_H.

Table 1. Specifications.

Component	Characteristics	quantity
Frame	Diagonal Wheelbase 450mm Frame mass 282g Takeoff mass 800g ~ 1600g	2 (top and bottom)
ESC	Current 30A OPTO Signal Frequency 30Hz ~ 450Hz Battery 3S ~ 4S LiPo	4+2
Motor	Stator size 22×12mm - KV 920rpm/V Propeller 10 × 3.8in; 8 × 4.5in	4+2
KK multi-controller V.5.5	4 rotors control integrated circuit Atmega IC	1
Propeller Pairs	10 in	6
Battery	11.1 V - 5000 mAh – mass 440g	1
Wheel	dimensions: 8 x 8 x 178 mm mass 9.07g	2
Spring	K=0.5 N/mm; C = 0.01 N/(mm/s); L_0 = 30 mm	2

3 Simulation results

Simulations of the wall-climbing drone have been developed firstly to size the actuation and springs allowing then the robot to stick and climb a vertical surface.

A simulation has been carried out considering motion sequence of the approach and contact to a vertical surface, as it is shown in Figure 3. For the proposed simulation, only the horizontal propulsion is taken into account, while the simulation results for the four propellers with vertical axis are not shown. The motion laws used to drive the climbing drone toward the wall is shown in Figure 4a. In particular, it is possible to appreciate the contact with the wall, then the horizontal propulsion force increases to get the drone closer to the wall. The distance from the wall is shown in Figure 4b. It is worth to note that the force of the propellers does not start from zero, because a starting value of the force is required for getting close to the wall. Subsequently, when the wheels get in contact with the surface this force grows.

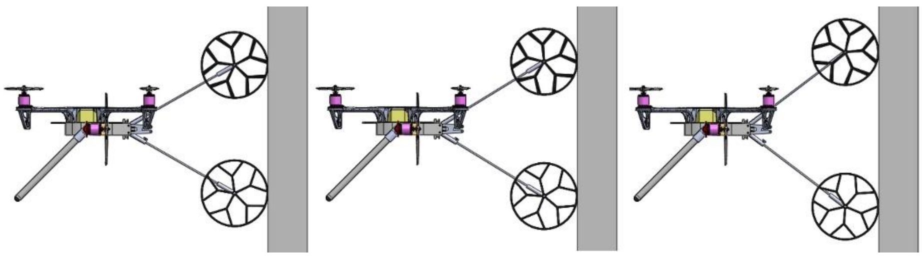
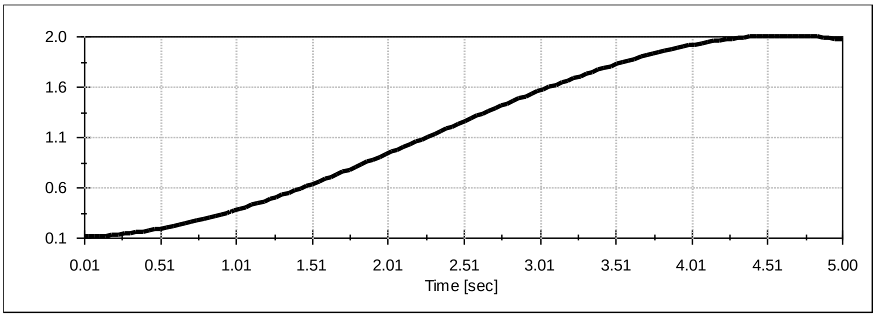
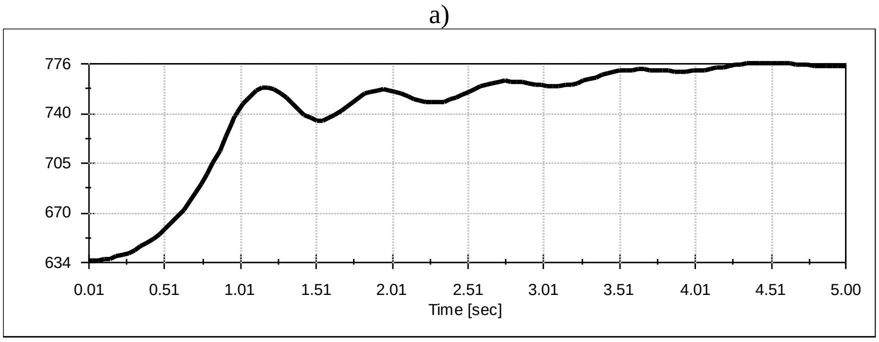


Fig. 3: Motion sequence of the simulation for the wall-climbing drone in Figure 1.



a)



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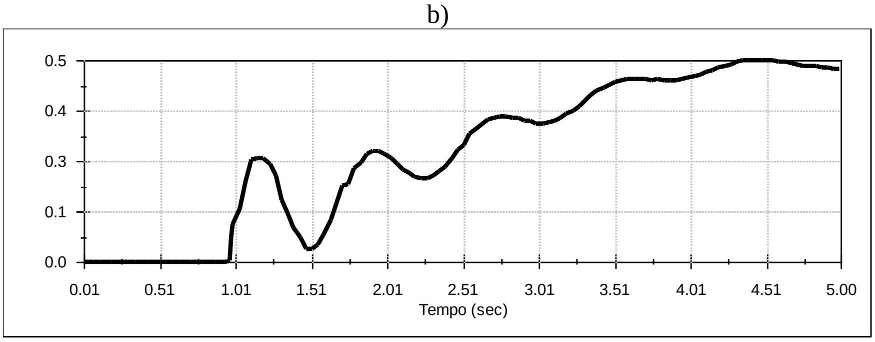
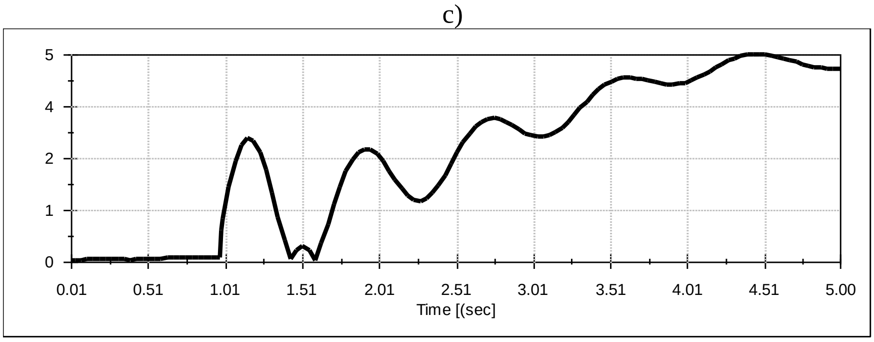


c)



d)

Fig. 4: Simulation for the contact: a) horizontal propulsion force F_H; b) distance from the wall D_w; c) wheel reaction force against the wall R_w; d) spring force F_s.

4 Mechatronic design

Figure 5 shows the built prototype, which is currently under testing to reduce masses and static and dynamic balancing. A scheme for the control of the propellers is reported in Figure 6. It is worth noting that this solution allows decoupling the control of the propellers with vertical axis and those with horizontal axis (labeled as motor 5 and 6 in Fig. 6), the latter used only when approaching to a surface. The idea of decoupled control strategies has been also used in [14-16] for the mechatronic design of multibody systems. The synthesis procedures for the mechanics are described in [17].

The drone Electronic Speed Controller (ESC) is a hard-working, powerful component that connects the flight controller to the motors. Given that each brushless motor requires an ESC, a quadcopter will require 4 ESCs. The ESC takes the signal from the flight controller and power from the battery and makes the brushless motor spin.

The ESC communicates with the control board using a Pulse Position Modulation PPM digital modulation technique. In particular, the FC (Flight Control) sends a sequence of square wave pulses to the ESC which, interpreting their position and / or duration (τ), varies the angular speed of the motors, Figure 6. The FC sends a pulse of period T and the duration τ in which the signal is high is the factor that determines the final angular speed of the motor. Having chosen motors with a maximum absorption of 10.6 A, an ESC of at least 20 A must be used. ESC can be programmed by specific software. The used KK multi-controller is a flight control board for remote control of multi-copters with 2, 3, 4 and 6 rotors, which is used to stabilize the drone during flight. It takes signals from the three gyros on the board (roll, pitch and yaw) and feeds the information into the Integrated Circuit (Atmega IC). The latter processes the information according the KK software and sends out a control signal to the (ESCs) which are plugged onto the board and also connected to the motors. Depending upon the signal from the IC the ESCs will either speed up or slow down the motors in order to establish level flight.

Fig. 5: Built prototype.

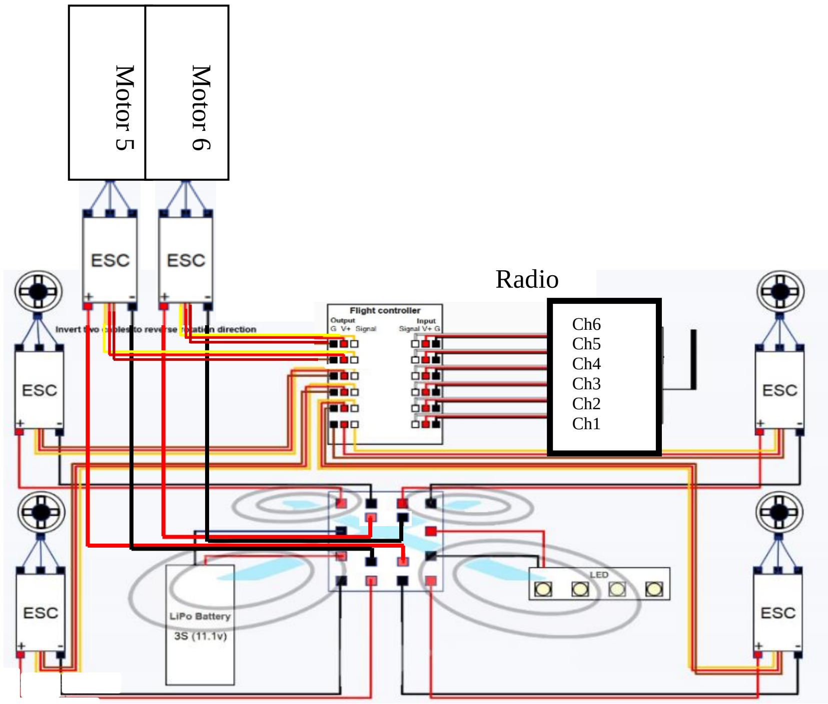


Fig. 6: A scheme of the control for the wall-climbing-drone.

5 Conclusion

In this paper, the design and first prototype are presented for a wall-climbing drone that can be used for inspection of structures and infrastructure. Simulation results of the system approaching a vertical surface are reported, they are used both in design stage, for sizing the legs and springs, and for defining the operations during the experiments. A first prototype has been built for experimental tests and it is currently under testing.

6 Acknowledgments

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