On the exploitation of differential aerodynamic lift and drag as a means to control satellite formation flight

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Abstract In order for a satellite formation to maintain its intended design despite present perturbations (formation keeping), to change the formation design (reconfiguration) or to perform a rendezvous maneuver, control forces need to be generated. To do so, chemical and/or electric thrusters are currently the methods of choice. However, their utilization has detrimental effects on small satellites' limited mass, volume and power budgets. Since the mid-eighties, the potential of using differential drag as a means of propellant-less source of control for satellite formation flight is actively researched. This method consists of varying the aerodynamic drag experienced by different spacecraft, thus generating differential accelerations between them. Its main disadvantage, that its controllability is mainly limited to the in-plain relative motion, can be overcome by using differential lift as a means to control the out-of-plane motion. Due to its promising benefits, a variety of studies from researchers around the world have enhanced the state-of-the-art over the past decades which results in a multitude of available literature. In this paper, an extensive literature review of the efforts which led to the current state-of-the-art of different lift and drag based satellite formation control is presented. Based on the insights gained during the review process, key knowledge gaps that need to be addressed in the field of differential lift in order to enhance the current state-of-the-art are revealed and discussed. In closer detail, the interdependence between the feasibility domain / the maneuver time and increased differential lift forces achieved using advanced satellite surface materials promoting quasi-specular or specular reflection, as currently being developed in the course of the DISCOVERER project, is discussed.

Keywords Satellite aerodynamics · differential lift · differential drag · formation flight control · propellant less control

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1 Introduction

Formation Flight (FF) of small satellites is a frequently discussed and investigated concept of distributing sensing applications among small satellites to address scientific objectives. Mission scenarios entailing multiple satellites offer significant enhancements and improvements in flexibility, robustness, and redundancy [1]. An up-to-date review can be found in [2].

Scharf et al. [3] define formation flying as: *"a set of more than one spacecraft whose dynamic states are coupled through a common control law"* [3]. Furthermore, the authors extend that, in particular, at least one member of the set (referred to as *deputy* within the scope of this paper (in

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literature also referred to as *chaser* or *slave*)) has to track a desired state *relative* to another member (referred to as *chief* (in literature also referred to as *target*)) and the tracking control law must depend upon this relative state. The second point is declared critical since it differentiates a formation from a constellation, e.g. the GPS satellites, in which a relative position is actively maintained, too, but the orbit corrections are solely based on an *individual* satellite's position and velocity (state) [3].

In planetary orbital environments (POE), one cannot define an arbitrary formation design but only one that is *legal*, i.e. permitted by the law of physics: *"To give an example: one cannot require two satellites to 'fly' side by side infinitely. Their paths will cross before they finish the first orbit. Nor can one require a satellite to 'fly' above or below another at the same speed. Satellites do not fly, they orbit"* [4]. Legal satellite formation flying designs can be derived using the linearized equations of relative motion of two objects under the influence of nothing but a point-mass gravitational field, commonly known as *Hill* [5] or *Clohessy-Wiltshire* equations (CW) [6] and expressed in the Local Vertical Local Horizontal (LVLH) rotating coordinate system centered at the reference spacecraft (*chief*). A detailed derivation of the CW equations can be found in [7]. Throughout the course of this paper, the LVLH coordinate system is defined following the definition of Vallado [7]: the $\hat{x}$-axis points from the Earth's center along the radius vector towards the chief satellite as it moves through the orbit. The $\hat{y}$-axis points in the direction of (not necessarily parallel to (in the case of non-circular orbits)) the velocity vector and is perpendicular to the radius vector. The $\hat{z}$-axis is normal to the orbital plane.

For the sake of simplicity, the derivation of the CW equations completely neglects natural perturbations. In reality, though, every orbital element dependent perturbation pulls the formation apart (certain invariant relative orbits exist [8] but they remain an exception). Thus, in order for the formation to keep its intended design despite present perturbation (commonly referred to as *formation keeping / maintenance*), or for any change in the formation design (*rendezvous maneuvers* or *reconfiguration*) control forces need to be generated. To this day the method of choice is to use chemical/electrical or cold gas thrusters. However, the limited availability of the propellant shortens the expected lifetime of a mission. This is especially critical in the case of CubeSats, since:

1. They are subjected to very stringent mass and volume constraints.
2. Constrains in volumes and pressures of stored propellant, nominally to protect the primary payload, can limit the capability and/or availability of on-board propulsion systems if they are launched as secondary payloads [9].
3. The related propellant exhaust might affect sensitive on-board sensors.

As a consequence, propellant less techniques to generate control forces are of greatest interest for the CubeSat community. As will be introduced in the next chapter, differences in the magnitude of lift and drag forces experienced by satellites travelling through Earth's atmosphere in Low-Earth Orbit (LEO) and Very Low-Earth Orbit (VLEO), the latter referring to *circular* orbits with a mean altitude lower than 450 km within the course of this paper, can be exploited as a means to control satellite formation flight. Moreover, other propellant less techniques, e.g. solar radiation pressure [10], the geomagnetic Lorentz force [11, 12] or inter-vehicle coulomb forces [13, 14], are envisaged as possible solutions to either reduce or even remove the need for an on-board propellant. However, they are not further considered in the course of this paper, as are aeroassisted orbit maneuvers or aerobreaking. For an excellent review, the reader is referred to the work of Walberg [15].

1.1 Differential Lift and Drag

The *aerodynamic drag* acting on a satellite can be expressed as a specific force (acceleration) as (Eq. 1-2) [7]:

$$\vec{a}_D = -\frac{1}{2}\frac{C_D A}{m}\rho|\vec{v}_{rel}|^2\vec{u}_D \tag{1}$$

with:

$$\vec{u}_D = \frac{\vec{v}_{rel}}{|\vec{v}_{rel}|} \tag{2}$$

Here, C_D is the drag coefficient, ρ the atmospheric density, m the mass of the spacecraft and A its cross-sectional area normal to the velocity vector. The velocity vector $\vec{v}_{rel}$ is measured relative to the atmosphere taking the Earth's rotation and wind into account [8]. In POE, the specific mechanical energy of a satellite is defined as (Eq. 3) [7]:

$$\xi = -\frac{\mu}{2a} \tag{3}$$

where μ is the gravitational constant and a the semi-major axis. As atmospheric drag dissipates energy from the system it inevitably causes orbital decay and eventually re-entry[1]. Therefore, it is an unwanted perturbation. The magnitude of the drag acceleration strongly depends on the design of the satellite, which is generally expressed in the so-called *ballistic coefficient* (BC) defined as the ratio $m/(C_D A)$. If

[1] At the same time, its kinetic energy is increased. This phenomena is often referred to as *satellite drag paradox* [16].

the BCs of two spacecraft differ, both experience different magnitudes of drag accelerations and the formation deteriorates over time. Vice versa, a desired differential acceleration between two satellites can be intentionally commanded via a well-chosen delta in their BCs. This method is commonly referred to as *differential drag* and was first introduced by C. L. Leonard in 1986 [17].

Varying the mass is in general an irreversible process and considered no option. However, there are several options available to reversibly adjust the surface area perpendicular to the flow. Leonard proposed to use dedicated drag plates (e.g. solar panels) and to adjust the magnitude of the drag acceleration by rotating the plates. The latter is visualized in Fig. 1, in which the chief is currently in a maximum drag configuration whereas the deputy aims to minimize drag as best as possible. In this case, the satellites are assumed to have a constant attitude which is controlled by other means. A second option frequently discussed is to rotate the satellite itself e.g. by using reaction wheels. The latter postulates that the satellite is asymmetrically shaped such that a noticeable difference in the corresponding surface area can be created. The reaction wheels are expected to be powered using solar panels so that no propellant is consumed. A third possible solution is to use a dedicated drag sail. However, different from a commercially available de-orbit sail, it needs to be able to be opened and closed multiple times (see e.g. [18]).

Despite its promising benefits the method entails several limitations:

1. The method is limited to VLEO and/or low LEO operations. As the density decreases with altitude, there is inevitably a maximum height for which a meaningful control authority is available.
2. The disturbance force caused by the J_2 effect of the Earth's oblateness [2] increases with the inter-satellite distance. Consequently, there exists a maximum separation distance (depending on the altitude) up to which the formation is controllable.
3. Every control action inevitable cause orbital decay and there is no option available to reverse this process.
4. The extended maneuver times renders the method infeasible for some applications.

Its main disadvantage, however, is that its control authority is (mainly) limited to the in-plane relative motion. The drag force in the out-of-plane direction (occurring for inclinations $i \neq 0$ due to the rotating atmosphere) is shown to be two orders of magnitude smaller even for highly inclined orbits [19] and unable to provide meaningful control authority. Also, a potential indirect out-of-plane maneuvering by an adjustment of the secular drift of RAAN caused by Earth's oblateness by changing the semi-major axis using drag can be envisaged but is neglected here.

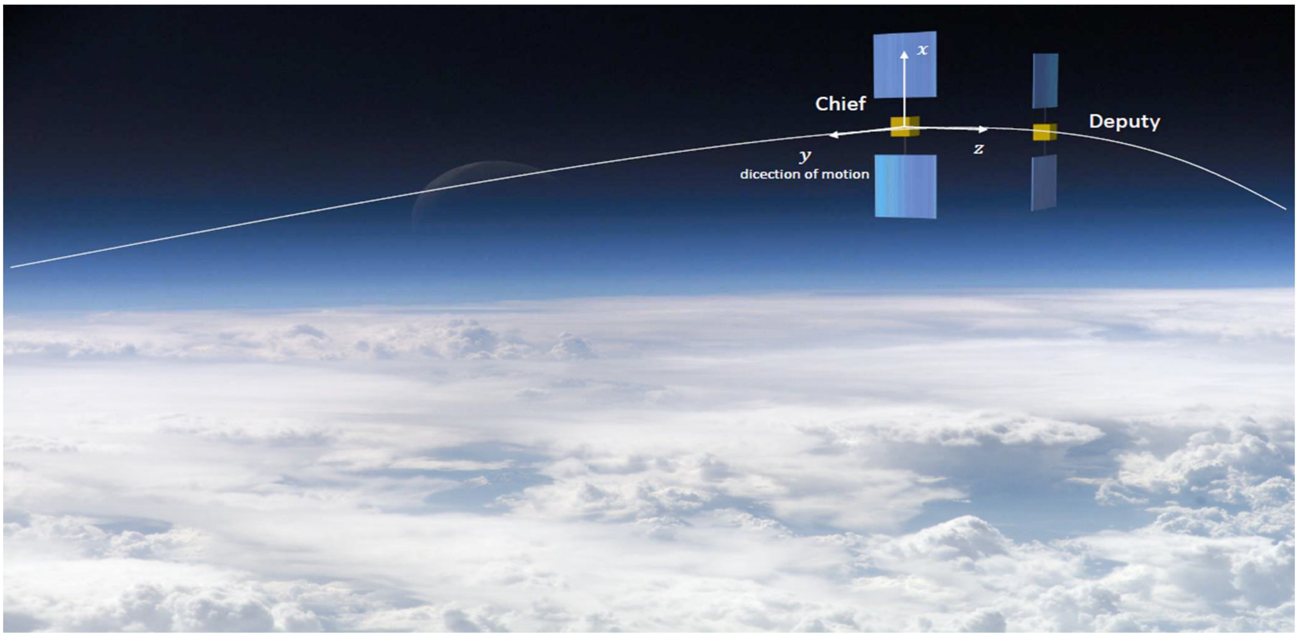

Fig. 1 Visualization of an in-plane formation [4], using the satellite's solar panel as dedicated drag / lift plates. The origin of the LVLH coordinate system is centred at the chief and the axes are as previously defined

[2] J_2 is the second order harmonic of Earth's gravitational potential field

To bypass this disadvantage, Horsley [20] proposed to use *differential lift* as a means to control the out-of-plane relative motion in 2011. Satellite lift, defined as the aerodynamic force acting perpendicular to drag, can be expressed as a specific force as (Eq. 4-5) [21]:

$$\vec{a}_L = -\frac{1}{2}\frac{C_L A}{m}\rho|\vec{v}_{rel}|^2\vec{u}_L \tag{4}$$

with:

$$\vec{u}_L = \frac{(\vec{v}_{rel}\times\vec{n})\times\vec{v}_{rel}}{|(\vec{v}_{rel}\times\vec{n})\times\vec{v}_{rel}|} \tag{5}$$

where C_L is the lift coefficient and $\vec{n}$ is the normal vector of the respective surface under consideration. All other parameters remain as previously defined. Most frequently, satellite lift (which acts perpendicular to drag) is considered to be negligible. This is because satellites that are spinning/tumbling or satellites with certain symmetrical shapes tend to have the effect of aerodynamic lift cancel out. In addition, the lift coefficients C_L experienced so far are noticeably smaller than the drag coefficients [20]. However, by intentionally maintaining a constant attitude relative to the velocity vector, the effects of aerodynamic lift is shown to essentially build up over time and generate measurable effects on the satellite orbit. This was first experienced during the analysis of the inclination of the S3-1 satellite in 1977 [22]. Moore studied the effects of aerodynamic lift on near circular satellite orbits in closer detail in 1985 [23].

Using a combination of differential drag and lift, all three translational degrees of freedom of the spacecraft relative motion become controllable. This can be mathematically expressed using the solutions to the *Schweighardt-Sedwig* (SS) equations [24, 25], which can be solved analytically. Although being surprisingly similar in form to the CW equations, the linearized equations are able to capture the influence of the J_2 potential. The solutions to an intermediate set of SS equations including differential lift and drag accelerations expressed in Eq. 6 - 14 are generally taken from Shao et al. [26] but presented in the notation proposed by Smith et al [27]. A slight correction had to be included to make the equations fully correct.

$$x = \bar{x} + \alpha \tag{6}$$

$$y = \bar{y} + \beta \tag{7}$$

$$z = \left(z_0 - \frac{a_z}{D^2\omega^2}\right)\cos(D\omega t) + \frac{\dot{z}_0}{D\omega}\sin(D\omega t) + \frac{a_z}{D^2\omega^2} \tag{8}$$

with $\bar{x}$, $\bar{y}$, α and β being defined as (Eq.7-10):

$$\bar{x} = \bar{x}_0 + \frac{A}{\omega}a_y t \tag{9}$$

$$\bar{y} = \bar{y}_0 + B\omega\bar{x}_0 t - \frac{A}{\omega}a_x t + \frac{AB}{2}a_y t^2 \tag{10}$$

$$\alpha = \left(\alpha_0 - \frac{Aa_x}{2c\omega^2}\right)\cos\left(\sqrt{\frac{2c}{A}}\omega t\right) + \left(\frac{\beta_0}{\sqrt{2cA}} - \frac{A^2 a_y}{2\omega^2}\right)\sin\left(\sqrt{\frac{2c}{A}}\omega t\right) + \frac{Aa_x}{2c\omega^2} \tag{11}$$

$$\frac{\beta}{\sqrt{2cA}} = \left(\frac{\beta_0}{\sqrt{2cA}} - \frac{A^2 a_y}{2\omega^2}\right)\cos\left(\sqrt{\frac{2c}{A}}\omega t\right) + \left(\frac{Aa_x}{2c\omega^2} - \alpha_0\right)\sin\left(\sqrt{\frac{2c}{A}}\omega t\right) + \frac{A^2 a_y}{2\omega^2} \tag{12}$$

The coefficients are defined as follows (Eq.13-14):

$$c = \sqrt{1 + \frac{3J_2 R_E^2}{8r_c^2}(1 + 3\cos(2i_c))} \tag{13}$$

$$A = \frac{2c}{2-c^2},\ B = \frac{2-5c^2}{2c} \text{ and } D = \sqrt{3c^2 - 2} \tag{14}$$

Here, c is the *SS coefficient* which takes the J_2 influence into account. A, B and D are auxiliary variables introduced to simplify the equations. R_E is the Earth's mean radius, ω is the angular velocity of the chief spacecraft's orbit, i_c its inclination and r_c its radius. x_0, y_0, z_0, $\frac{\dot{z}_0}{D\omega}$, α_0 and $\frac{\beta_0}{\sqrt{2cA}}$ are the initial conditions. a_x, a_y, a_z are the relative accelerations generated using differential lift and drag. The equations are expressed in the LVLH coordinate as previously defined. In the linearized equations, the in-plane relative motion is completely decoupled from the out-of-plane relative motion and can be decomposed into a double integrator modelling the average location of the deputy with respect to the chief ($\bar{x}, \bar{y}$) as well as a harmonic oscillator modelling its eccentricity e ($e = \sqrt{\alpha^2 + \beta^2/2cA}$). The out-of-plane motion solely consists of a non-secular harmonic oscillator.

The influence of constant differential lift and drag on the phase planes is displayed in Fig. 2 (figure design taken from [26]). As an understanding of the influence is critical to follow the gap analysis later on (chapter 0), the main features will be discussed shortly. Taking Eq. 6 - 14 into account, it follows that the $\bar{x}$ can be only influenced by a differential drag acceleration a_y. The latter causes the state to move along the depicted parabolas in the $(\bar{x}, \bar{y})$ phase plane. The parabolas passing through the origin (indicated in bold in Fig. 2 (b)) are the so-called switch curves well-known from the time optimal control of a double integrator. At the same time, the acceleration causes the state in the $(\alpha, \beta/\sqrt{2cA})$ plane to follow a stable circular motion with the circle's center being shifted towards a positive (negative) $\beta/\sqrt{2cA}$) value proportional to the magnitude of the available positive (negative) differential drag acceleration a_y. A differential lift acceleration in the radial direction a_x causes a similar circular motion of the $(\alpha, \beta/\sqrt{2cA})$) plane, however now with the centers being shifted towards a positive (negative) alpha value, dependent of the respective sign of a_x. This causes the $\bar{y}$ to change linearly with time and proportionally to the magnitude of a_x. In the depicted case, the deputy was initially located at the origin. With no acceleration being present, the $(\alpha, \beta/\sqrt{2cA})$ states circulate around the origin. The equations also show that in the linearized case, the out-of-plane motion is completely decoupled from the in-plane motion, differential lift in the $\hat{z}$-direction does not interfere with the in-plane relative motion at all. Vice versa, aerodynamic forces in the $\hat{x}$- / and $\hat{y}$-direction have no effects on the out-of-plane relative motion. Consequently, for a differential lift acceleration in the out-of-plane direction a_z, only the $(z, \dot{z}/D\omega)$ plane is of interest. This shows the characteristic pattern of a harmonic oscillator with the center of the circle being shifted towards a positive (negative) z value depending on the sign of the respective differential acceleration. With no acceleration being present, the state circles around the origin in a stable motion. Noticeably, Fig. 2 displays the influence of *constant* differential accelerations causing the circles in phase planes a) & b) right side as well as c) to be concentric. For varying accelerations, the centers of the respective circles shift accordingly.

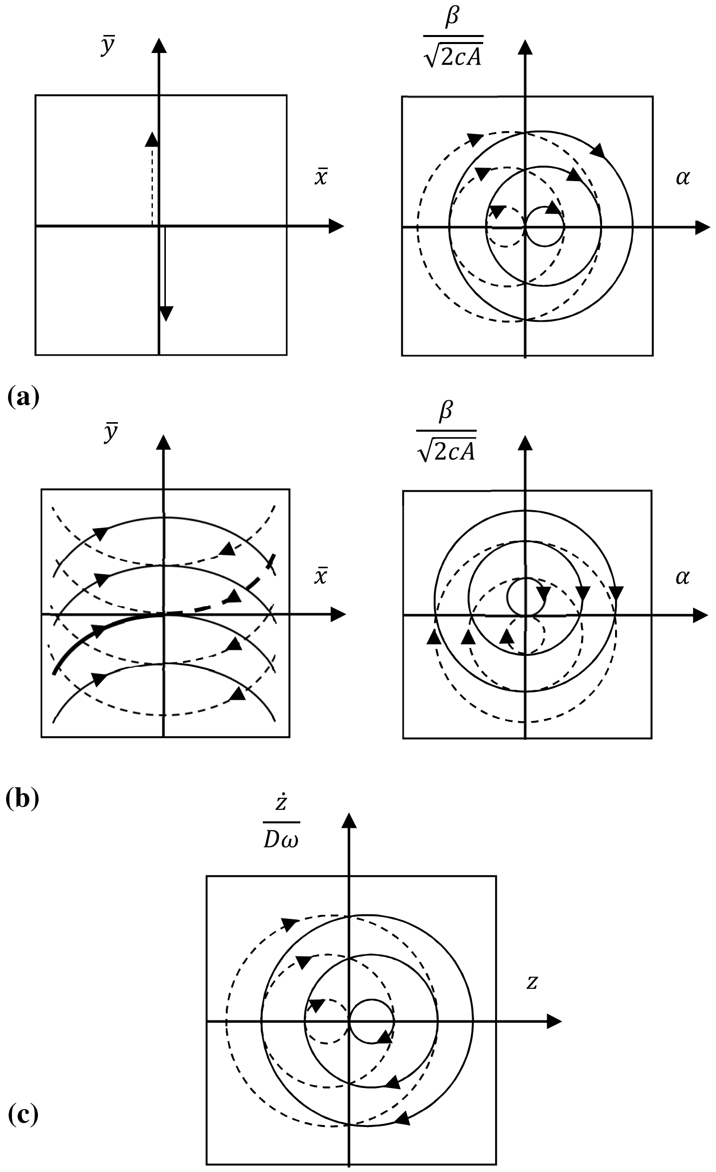

Fig. 2 Phase plane for *constant* differential accelerations in **(a)** the x-direction, **(b)** the y-direction and **(c)** the z-direction. A positive (negative) acceleration causes the state to move along the solid (dashed) trajectories. Figure design taken from [26]

2 Literature review

Because of its promising benefits, differential drag and lift methods were studied by a number of researchers for formation keeping / formation maintenance, rendezvous scenarios and re-phasing / reconfiguration purposes. In order to get a full picture of the developments and the current state-of-the-art, an extensive literature review was conducted. The main contributions leading to the state-of-the art are presented in the next sub-chapters. On a first level, the developments are separated according to the underlying force which is exploited (drag or drag and lift). On a second level, the publications are structured according to their formation flight scenario, which in the further case of this article are defined as follows:

1. *Rendezvous Scenario:* The aim of the rendezvous scenario is to zero out the relative position and velocity of two or more spacecraft.
2. *Formation Maintenance*: The aim of formation maintenance is to best possibly maintain a desired formation geometry despite present perturbations.
3. *Formation Reconfiguration*: The aim of formation reconfiguration is to change the design and/or size of the formation.

Within the respective subcategories, the developments are listed chronologically. Noticeably, this review focusses on the theoretic developments of the control theories and does not discuss project related publications. Also, using BC modifications for *reentry point targeting* [28–32], as it is frequently discussed, is not included since it does not belong in the classical field of differential lift and drag methods. Due to the ongoing research efforts and the multitude of available publications, the author can at no means guarantee for the completeness of the presented set of literature. However, the provided review most certainly covers the main efforts and provides a valuable overview of the progressions made. Unfortunately, some topic related articles were found but not accessible to the author [33–38].

2.1 Differential Drag

2.1.1 Rendezvous Scenario

In 1986, Carolina Lee Leonard [17] published her pioneering work in which she used the CW equations to decompose the in-plane relative motion into a double integrator as well as a harmonic oscillator. For each system alone the time-optimal control law is well known, using *switch curves* in the phase plane. Leonard combined both control laws in such way that all states are driven to the origin simultaneously [39]. The main control law drives the average position of the deputy to the chief while minimizing the eccentricity (phase one). The eccentricity-minimizing control scheme is activated once the average position of the deputy is at the chief (phase two); its purpose is to reduce the eccentricity of the deputy as much as possible without jeopardizing its final average position. Palmerini et al. [40] used a genetic algorithm to develop a control scheme based on differential drag using the Carter-Humi equations [41] (2005). In 2008, B. Kumar and Ng [42] published a first attempt to enhance Leonard's controller and to make it applicable in a realistic mission scenario. In the same year, Bevilacqua and Romano [43, 44] proposed to improve Leonard's algorithm by replacing the CW equations by the recently developed SS equations. Thereby, the influence of the J_2 effect is taken into account. Furthermore, they developed an entirely analytic maneuver routine which is able to deal with an arbitrary number of spacecraft. In a follow up publication published in 2010, Bevilacqua et al. [45] proposed a two-phase hybrid controller. In 2011, Pérez and Bevilacqua enhanced the approach from [43, 44] in two follow up publications: In [46], the real, nonlinear and perturbed trajectory is regularly compared to the guidance trajectory designed using principles developed in [44]. Once an error threshold is met, a new guidance based on the current relative position and velocity is calculated. Using this *feedback* approach, the deputy is guided within close proximity of the chief despite the present perturbation and nonlinearities. In [47], the authors presented a *Lyapunov control* approach inspired by the previous work of one of the authors [48] to force the non-linear system to track the analytically created guidance trajectory. In 2013 and 2014, the authors enhanced the method in two successive follow-up publications [49, 50] making the *Lyapunov control adaptive*. In 2012 Lambert et al. [51] built upon B. Kumar and Ng's work [42] and increased the applicability of Leonard's approach under practical conditions. In the same year, Dell'Elce and Kerschen [52, 53] presented a two-step off-line optimal control strategy for a rendezvous maneuver in the course of the QB50 project proposed by *Von Karman Institute for Fluid Dynamics* [54]. Though being achieved using a completely different approach, the solution is consistent with the oscillation reduction controller implemented by Lambert et al. [51]. In the years 2014 and 2015, Dell'Elce and Kerschen [55–57] improved their optimal control algorithm based on *model predictive control* (MPC) in three successive publications. In 2015, Spiller et al. [58–60] proposed an approach to search the suitable solution space using *inverse particle swarm optimization* (iPSO). Mazal et al. [61] included (bounded) uncertainties in the drag acceleration in the development of controller for rendezvous maneuvers in 2016. In the same year, Cho et al. [62] developed a chattering free *sliding mode controller* based on the insights from [57] and Peréz and Bevilacqua [63] proposed using *artificial neuronal networks* to predict the future behavior of the density in order to enhance the fidelity of the created guidance trajectories. The method was further advanced to reflect the dependence on spatial and temporal differences, donated as *spatial-temporal resolution*, in a follow-up publication by Guglielmo et al. [64] published in the same year.

The developments on the adaptive Lyapunov control strategies [49, 50] combined with the work on using artificial neuronal networks resulted in the PhD dissertation of Pérez [65] in 2013. Dell'Elce [66] successfully obtained his PhD for his contributions to uncertainty quantification and optimal control of satellites in the atmosphere in 2015. For his achievements in the field of optimal control using *swarm intelligence*, Spiller [67] received his PhD in 2018.

2.1.2 Formation Keeping / Maintenance

In a follow-up paper to her master's thesis, Leonard et al. [39] used the insights gained within the thesis to addressed orbital formation keeping in 1987. Similar analysis was presented 1988 by Mathews and Leszkiewicz [68], Aorpimai et al. [69] (1999) as well as by Folta et al. [70] in 1996. In 2004, Fourcade [71] analyzed using differential drag to control the mean nodal elongation between several satellites. Jigang and Yulin [72] developed a control method for the maintenance of co-plane formation based on a phase-plane analysis in 2006. Further progress in the field was made in the same year by a thesis from the *Air Force Institute of Technology* in which Wedekind [73] was able to mitigate the effects of drag on different (uncontrolled) formation geometries by using a simple *proportional-integral* (PI) controller. With regard to the JC2Sat-FF mission, B. Kumar et al. [74] investigated the feasibility of using differential drag and included a detailed analysis of the affecting parameters (2007). In his master's thesis from 2011, Bellefeuille [75] compared different control techniques, such as an energy matching *proportional-integral-derivative (PID)* controller or an *Floquet-Lyapunov controller*, for the formation maintenance using differential drag. Reid and Misra [76] modified the Schweighardt-Sedwig equations to include the effect of differential drag and extended their approach to orbits of small eccentricity (2011). In a successive second step, they developed a simple panel shifting scheme in order to maintain a projected circular formation. Zeng et al. [77] proposed a new control scheme for formation keeping, amongst others including the time-optimal aerodynamic control (*switch planes*) for the along-track separation in 2012. K. Kumar et al. [78] analyzed using aerodynamic forces as well as solar radiation pressure as a means of control for formation maintenance in 2014. In 2015, Ben-Yaacov et al. [79] developed a method to examine the differential-drag based cluster flight performance in the present of noise and uncertainties. The method chosen for the uncertainty quantification s the *Linear Covariance Analysis*. Shouman and Atallah [80] developed a LQR control law for the maintenance of a circular formation based on the SS equations and validated their approach in a high fidelity propagator (2016).

2.1.3 Reconfiguration

Hajovsky [81] used the CW equations to develop a *linear-quadratic terminal (LQT)* controller for reconfiguration purposes in 2007. In his dissertation published in 2011, Varma [82] addressed using aerodynamic drag as well as solar radiation pressure to control satellite formation flight. He developed control algorithms based on *adaptive sliding mode control* techniques and validated them for formation maintenance as well as reconfiguration using dynamic simulations. In addition, he investigated the feasibility of multiple satellite formation flying and reconfiguration. In 2013, Pérez and Bevilacqua [83] used the *adaptive Lyapunov control* approach developed for rendezvous scenarios [49, 50] for the control of fly-around and re-phasing maneuvers. In 2014, Bevilacqua [84] presented a framework combining analytical guidance solutions for short distance re-phasing based on along track, on-off control (developed in [85]) with the adaptive Lyapunov control method presented in [49, 50]. The guidance is created using *input-shaping*. In 2015, Pastorelli et al. [86] proposed a novel technique to perform deputy-chief spacecraft relative maneuvers while simultaneously stabilizing the deputy's attitude. The conducted analysis contained rendezvous as well as re-phasing maneuvers. In 2017, Spiller et al. [87] presented an approach to exploit atmospheric drag and solar radiation pressure for circular formation reconfiguration as well as an along-track reconfiguration. Again, iPSO is used.

2.2 Differential Lift and Drag

2.2.1 Rendezvous Scenario

Even though the method of differential drag is being actively researched since 1986, it was not until 2011 that Horsley et al. [20, 88] proposed atmospheric lift as a means to control the out-of-plane motion in order to achieve a rendezvous in all three translational degrees of freedom. In a first publication, Horsley [20] assumed that the in-plane motion has already been controlled by other means and focusses on controlling the residual harmonic motion in the out-of-plane direction ($\hat{z}$-direction). Combining the results from Leonard et al. [17, 39] and the insights presented by Horsley [20], three successive phases are necessary to achieve complete rendezvous solely exploiting aerodynamic forces. These three phases are referred to as follows in the further course of this paper:

1. In the *first phase*, the double integrator of the in-plane relative motion is controlled (average position).
2. In the *second phase*, the harmonic-oscillator of the in-plane relative motion is controlled (eccentricity).
3. In the *third phase*, the harmonic-oscillator of the out of plane relative motion is controlled.

Since the in-plane relative motion is coupled, the eccentricity (phase two) can be controlled using either differential drag or lift (see Fig. 3 and 4). In a follow up publication Horsley et al. [88] compared both possible control options for the second phase. For the chosen set of initial condition analyzed, differential lift lead to a 40% shorter maneuver time. This is because, in this case, the symmetric nature of the drag-only maneuver requires an excessive coast period whereas the in-plane differential lift maneuver does not require any coasting time and the control can be executed immediately. In addition, orbital decay could be reduced by about 30%.

In 2015, Shao et al. [26] enhanced Horsley et al.'s algorithm by replacing the CW equations with an intermediate set of the SS equations (see Eq.5 to Eq.13). Thereby, the influence of the J_2 effect is taken into account and the accuracy increased. The general structure of the control algorithm remained unchanged.

Only recently (2017), when analyzing the practicability of the just described control algorithms, Smith et al. [27] revealed that both inevitably lead to collisions, potentially causing catastrophic damage to the spacecraft. Thus, the authors concluded that the existing differential lift-based rendezvous algorithms are 'impractical'. The issue could be circumvented by rearranging the order in which rendezvous is achieved: In the reworked order, the out-of-plane relative motion is zeroed out before the oscillation motion of the in-plane relative motion (eccentricity) is. By doing so, collisions are eliminated. In addition, the publication includes an analysis of the feasibility of achieving rendezvous for a variety of different initial conditions via a Monte Carlo approach. The analysis showed that Horsley et al.'s statement, according to which the maneuver time of phase two can be reduced by using lift rather than drag, is only true for a very limited set of initial conditions. And even if, the ability to perform the second phase faster does not guarantee that the total rendezvous time is reduced. In addition, the analysis revealed that even though it is possible to use differential lift during the second control phase, it is generally an inferior option compared to differential drag both in terms of maximum maneuver range as well as total rendezvous time. Therefore, the authors conclude that in planning practical spacecraft rendezvous, differential drag should be considered for in-plane components of rendezvous due to its higher reliability, larger practical range, and generally faster maneuver times [27].

2.2.2 Formation Keeping / Maintenance

In 2017, Shao et al. [89] presented a control approach for formation keeping via aerodynamic forces using a controller design developed using *Lyapunov principles* from [1]. The presented controller forces the satellite relative motion to track a predefined guidance generated using the CW equations. In addition, the paper analyses the boundary conditions under which the methodology is feasible. The two limits considered, resulting from a trade-off between disturbing J_2 force and available control authority, are the maximum maneuver altitude and the maximum inter-satellite distance (formation size). In the same year, Sun et al. [90] investigated the problem of controlling both, translational and rotational motions for small-satellite formation using aerodynamic drag and lift. In an example test case, the orbit controller maintains the formation during the maneuver whereas the attitude has to be constantly adjusted in order to accurately point in the direction of the chief. In follow-up publications, Sun et al. [91, 92] presented a *neural network-based adaptive sliding mode* controller which accounts for system uncertainties and external perturbations.

In 2018, Ivanov et al. [93] presented an approach using a *linear-quadratic regulator* (LQR) for the maintenance of a tetrahedral configuration using aerodynamic forces. Since in this case there exist three desired trajectories for each satellite (relative to each of the other satellites), a *decentralized control* approach was developed in which each satellite is controlled independently. Using mean tracking error vectors, the relative trajectory of an individual satellite converges to some average desired relative trajectory. In the end all of the relative deviations decrease and the desired formation geometry is established. The latter presents the first control approach exploiting aerodynamic lift and drag including multiple satellites.

2.2.3 Re-Phasing / Reconfiguration

In 2018, Ivanov et al. [94] presented a *linear-quadratic regulator* (*LQR*) based control algorithm for satellite formation reconfiguration. The ability of the controller to transit the formation from one closed relative trajectories into another is validated via numerical simulations.

2.3 Conclusion of literature review: State-of-the-Art

Differential drag has been investigated continuously starting as early as 1986 with Leonard's publication [17] and since then substantial and significant progress has been made:

1. Robust control concepts have been proposed.
2. The influence of uncertainties and noise have been assessed.
3. Robust maneuver planner which guarantee the feasibility of the trajectory over an arbitrary (user-defined) portion of the uncertain set have been developed.
4. The methodology has been verified using high-fidelity propagators calculating the relative motion from the

individual real, perturbed trajectories of both spacecraft subjected to all major perturbations.
5. The ORBCOMM constellation has successfully applied the methodology for formation keeping purposes in reality [95].

Due to the just listed progress, the state-of-the-art of differential drag in terms of control theory is advanced. Especially the rendezvous scenario has been dealt with in depth (see Tab. 1). However, there is still a lack considering the development of the respective hardware required to realize the proposed control strategies. In particular, the frequently used bang-bang type control, which includes the assumption that the attitude is controlled by other means and that the drag magnitude can be changed discrete and instantly, is more of theoretical nature and not realizable as such. Therefore, the focus of future research efforts should be shifted from control theory development towards an transformation of the theoretical approaches into flyable hardware.

Tab. 1 Summary of the conducted literature review

	Differential Drag	*Differential Lift*
Multiple satellites	[43–45, 67]	[93]
Advanced maneuver planning	[55–60, 63–67, 87]	-
Robust control concepts	[46, 47, 49, 50, 55–57, 61–66, 78, 79, 82, 83]	[90–92]
Uncertainties & Noise considered	[42, 45, 55–57, 61, 64, 66, 74, 79]	[91, 92]
Verified in high fidelity propagator	[42, 45–47, 49, 50, 55–59, 61–66, 74, 78–80, 82, 83, 87]	[90–92]
Verified in reality	[95]	-
Rendezvous	[17, 40, 42–47, 49–53, 55–67]	[20, 26, 27, 88]
Formation Keeping	[39, 68–70, 72–80]	[89–93]
Reconfiguration	[81–84, 86, 87]	[94]
Total number of publications reviewed	50	10

Differential lift has not been considered an option until 2011 [20] and, unlike in the field of differential drag, the progress made since then is very limited: mainly linearized models as well as a constant density assumption have been used to gain first insights and derive analytically created open loop control sequences, out of which several even caused collisions. Apart from the publications by Sun et al. [90–92], neither robust control methods nor uncertainties or noise have been considered at all (see Tab. 1). Thus, the current state-of-the-art is low and there exist several knowledge gaps which have to be addressed in order to make the methodology applicable in a real world scenario. In the next chapter, the insides gained via the conducted literature review are used to identify and formulate the key gaps and depicts possible options on how they can be addressed. To sum up the performed review process, the following table (Tab. 1) lists all reviewed publications according to criteria which are necessary to make the methodology applicable in reality and thus considered representative for the current state-of-the-art of the methodologies.

3 Key Knowledge Gaps of Differential Lift

The research efforts conducted so far were mainly focusing on differential drag and only very little insight into differential lift is available. This was taken as an occasion to focus this chapter on revealing key gaps in the field of differential lift which have to be addressed in order to enhance the current state-of-the-art and to make the methodology an suitable option for propellant-less control of satellite formation flight in a real mission scenario.

Generally, it needs to be recorded that apart from the studies presented in [93], the application of differential lift were only studied for the relative motion of two satellites. Thus, an extension of the method towards including multiple ($2+n$, $n \in \mathbb{N}$) satellites could have a significant contribution to potential practical application of the concept. The latter also promotes the development of *collision avoidance* techniques.

3.1 Feasibility Domain

Differential lift is a promising method since it not only enables to control all three translational degrees of freedom (in combination with differential drag) but also potentially to reduce the orbital decay compared to a purely differential drag based maneuver. However, as the analysis conducted by Smith et al. [27] has shown, using differential lift for controlling the eccentricity of the in-plane relative motion is an inferior approach compared to using differential drag both in terms of maximum range as well as of resulting maneuver time. Its reduced control authority limits the feasibility domain of initial conditions that lead to a successful rendezvous.

Following the notation from [27], the term *feasibility domain*, as it is referred to in the further course of this paper, is defined as the maximum inter-satellite distance in the $(\alpha, \beta/\sqrt{2cA})$ plane for which the control algorithm leads to a successful rendezvous.

Tab. 2 Orbital elements of the chief satellite used for the feasibility domain analysis

Element:	*Unit*	*Value*
a	km	6778.137
e	-	0
i	°	10
ω	°	130
Ω	°	45
M	°	45

The latter is visualized in Fig. 3 using a Monto-Carlo based approach similar to the research conducted in [27] but using the same orbital elements (see Tab. 2) and available differential drag and lift values as proposed in [26] ($|a_z| = |a_x| = 9 \cdot 10^{-6}\ m/s^2$, $|a_y| = 4 \cdot 10^{-5}\ m/s^2$).

A red dot indicates a non-successful rendezvous in either case, a green dot a case in which differential drag leads to rendezvous but differential lift fails and a blue dot consequently the case in which both, differential lift and drag, lead to a successful rendezvous. The resulting feasibility domain for differential drag is indicated using a dotted line, for differential lift using a dashed line. Needless to say, these values are only valid for the analyzed orbit and strongly vary with altitude. It can clearly be seen that the feasibility domain of using differential drag is distinctively larger then when using differential lift.

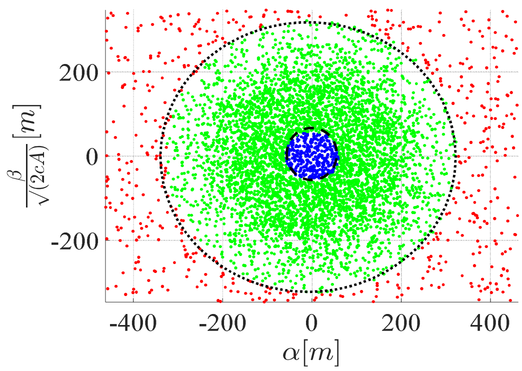

Fig. 3 Visualization of the feasibility domain for the eccentricity control phase using drag (green) and lift (blue). Non-successful rendezvous are marked in red. Feasibility domain of differential drag indicated in dotted lines, of differential lift in dashed lines [96]

As Smith et al. state: *"The condition for successful rendezvous using Horsley's or Shao's et al.'s algorithm for phase 2 is dependent on the magnitude of the α and $\beta/\sqrt{2cA}$ components at the start of phase 2. [...] the maximum range for the magnitude of the α and $\beta/\sqrt{2cA}$ components at the start of phase 2 is approximately 35 m for successful rendezvous for both Horsley's and Shao's algorithm."* [27]. Therefore, when planning practical spacecraft rendezvous Smith et al. recommend that differential drag should be used for controlling the eccentricity due to its higher reliability, larger practical range, and generally resulting faster maneuver time. Whereas these insights are certainly true for the analyzed boundary conditions, there are different options available to increase the feasibility domain. Two different options will be discussed in the following.

3.1.1 Sawtooth Pattern

A first option is to refine the rendezvous algorithm during phase one so that it decreases the residual values of α and $\beta/\sqrt{2cA}$ at the beginning of phase two. Since the latter is the key criterion for the maneuver success, this inevitably increases the feasibility domain.

A suitable option is to implement a so called *sawtooth pattern* during phase one, which was originally developed by Leonard et al. [17, 39] using the CW equations. The basic idea behind is as follows: once the average position is moving towards the origin, the control law differs from the minimum time solution of a double integrator in order to reduce the eccentricity. In the case of the SS equations, the rate of change of the eccentricity slightly deviates from Leonard's solution (see Eq. 13), but her general statement according to which: *"[...] the eccentricity is reduced whenever the control a_y has the same sign as α "* [39] is still valid (Eq. 15):

$$\frac{d(e^2)}{dt} = -\frac{\sqrt{2cA^3}}{\omega} a_y \alpha \tag{15}$$

For both values to have the same sign, a_y must change sign when α changes sign, which is twice per orbit. Doing so, the state moves in a sawtooth pattern towards the appropriate switch curve in the $(\hat{x}, \hat{y})$ plane. Since the updated control differs from the time-optimal solution, this leads to higher maneuver times.

Both, Horsley et al. and Shao et al. neglected a sawtooth pattern in their algorithms and consequently it was not part of the analysis conducted by Smith et al. Thus, there is currently no insight on how this method could increase the feasibility domain.

3.1.2 Increased Lift Forces

A second possible option to enlarge the feasibility domain is to increase the control authority of differential lift by developing enhanced materials targeting to increase the magnitude of the available lift forces.

The DISCOVERER project[1] [97], a Horizon 2020 funded research project consisting of nine international partners including those in the author list, aims to radically redesign Earth observation satellites for sustained operation at much lower altitudes than the current state of the art [98] by using a combination of new aerodynamic materials, aerodynamic control and atmosphere-breathing electric propulsion (ABEP) for drag-compensation [99]. One main goal is to identify and develop materials which encourage specular or quasi-specular reflection [97].

The residual atmosphere above 200 km is so rarefied that the mean free path of the gas molecules strongly exceeds the typical dimensions of a satellite [97]. Thus, it cannot be considered a continuous fluid but a free molecular flow (FMF). In this FMF regime, the so-called regime of extreme rarefaction [100], the residual atmospheric gas needs to be considered particulate in nature and features negligible few collisions between constituent molecules. Thus, the incident flow can be assumed entirely undisturbed by the presence of the body [100]. As a consequence, the forces and torques occurring on a free body under FMF conditions are a result of the energy exchange taking place between the incident gas particles and the external surfaces. These Gas-Surface-Interactions (GSI) are dominated by the material chemistry with the predominant gas species in the VLEO range, *atomic oxygen*, adsorbing to, and possibly eroding, the surface [97].

The type of reflection is known to be dependent on surface roughness/cleanliness, surface molecular composition and lattice configuration, surface temperature, incident gas composition and velocity and angle [97]: *"When the incoming molecules strike a clean surface, they are reemitted near the specular angle with a partial loss of their incident kinetic energy. The fraction of the incident energy lost depends very much on the mass of the incoming molecule. However, when the surface becomes heavily contaminated with adsorbed molecules, the incident molecules are reemitted in a diffuse distribution, losing a large portion of their incident kinetic energy. Thus, adsorbed molecules increase energy accommodation and broaden the angular distribution of molecules reemitted from surfaces"* [101].

This phenomena can be described in its entirety via three different accommodation coefficients. The *energy / thermal accommodation coefficient* α expresses how close the kinetic energy of the incoming molecules are adjusted to the thermal energy of the surface. It is defined as [102] (Eq. 16):

$$\alpha = \frac{E_i - E_r}{E_i - E_w} = \frac{T_i - T_r}{T_i - T_w} \qquad (16)$$

where E_i is the kinetic energy of the incident molecule, E_r is the kinetic energy of the reemitted molecule; and E_w is the kinetic energy the reemitted molecule would have if it left the surface at the surface (wall) temperature. The subscripts of on the temperatures refer to the same meaning. *"In other words, the accommodation coefficient indicates how closely the kinetic energy of the incoming molecule has adjusted to the thermal energy of the surface"* [103].

The momentum transferred to the surface is specified by momentum accommodation coefficients. Maxwell introduced the momentum accommodation coefficient, f, defined as the fraction of molecules that reflect diffusely, the remainder, $1 - f$, being reflected specularly [104]. In more recent developments, two different accommodation coefficients are used, one for tangential and one for normal momentum [102]. The *tangential* (Eq. 17) and *normal* (Eq. 18) *momentum accommodation coefficients* are defined as (Eq.16-17) [100]:

$$\sigma = \frac{\tau_i - \tau_r}{\tau_i - \tau_w} \qquad (\tau_w = 0) \qquad (17)$$

$$\sigma' = \frac{p_i - p_r}{p_i - p_w} \qquad (18)$$

τ and p are the tangential and normal momentum coefficients and the subscripts $_i$ and $_r$ refer to the incident and reflected flux. τ_w and p_w denote the tangential and normal momentum coefficients of the molecules which are reemitted with a Maxwellian distribution at the surface temperature T_w.

For complete diffuse reflection, where the velocities of the reflected molecules are centered around the surface normal vector in a cosine distribution (see Fig. 4), $\tau_r = \tau_w = 0$ and $\sigma = 1$ regardless of the degree of thermal accommodation [102]. If any specular reflection occurs, the value of σ depends on the degree of thermal accommodation via τ_r. If no thermal accommodation occurs and there is complete specular reflection, $\tau_r = \tau_i$ and $\sigma = 0$.

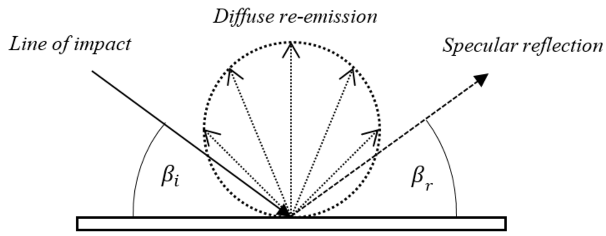

Fig. 4 Visualization of the two different reflection types

[1] *Disruptive Technologies for Very Low Earth Orbit Platforms*, https://discoverer.space/

For completely diffuse reflection along with complete thermal accommodation, $\sigma' = 1$; for completely specular reflection and no thermal accommodation, $\sigma' = 0$. For any type of reflection between these two extremes, σ' depends on the degree of thermal accommodation that occurs. This is different for σ which is equal to one for completely diffuse reflection regardless of the degree of thermal accommodation which occurs and depends on the degree of thermal accommodation only when part of the reflection taking place is specularly [102]. For clarity, from $\sigma' = 0$ (specular reflection with no thermal accommodation) only the conservation of the norm of the normal momentum follows but not of the momentum's direction, which is changed during the reflection (see Fig. 4). For the hypothetical case of an entirely specular reflection with vanishing energy exchange $\alpha = \sigma = \sigma' = 0$, for entirely diffuse reflection which has been completely accommodated to the surface temperature $\alpha = \sigma = \sigma' = 1$ [100]. Whilst the fundamental molecular interactions of atomic oxygen with spacecraft surfaces are poorly understood, its impact on the aerodynamic performance of a surface is known to be significant: Adsorbed molecules increase energy accommodation and broaden the angular distribution of molecules reemitted from the surfaces [103].

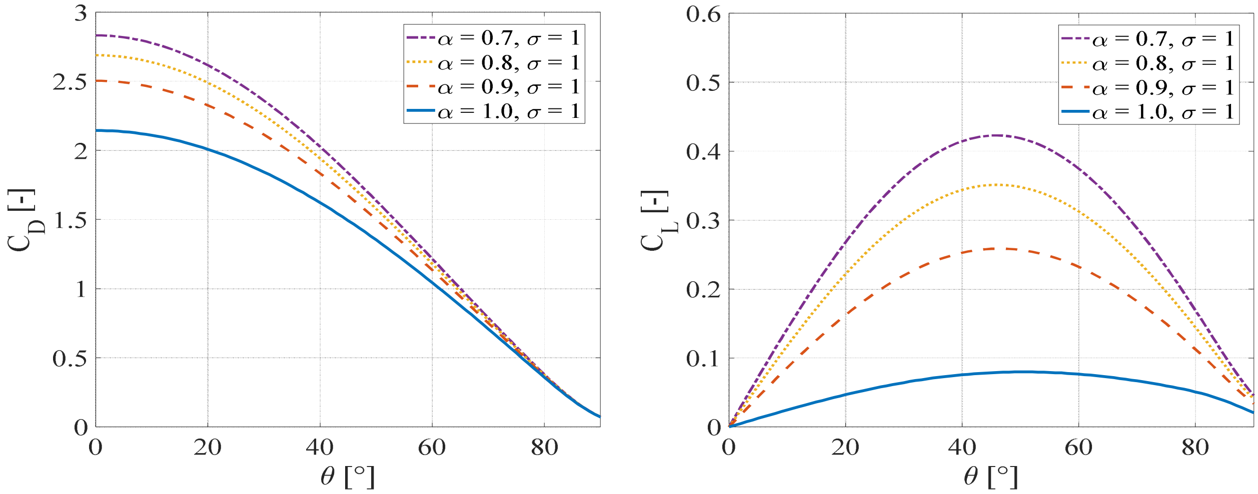

Fig. 5 Drag and lift coefficients for a flat plate at different incidence angles θ and energy accommodation coefficients α calculated using Sentman's GSI model [102], which assumes diffuse reflection, at an altitude of 400 km and a wall temperature T_w of 300 K

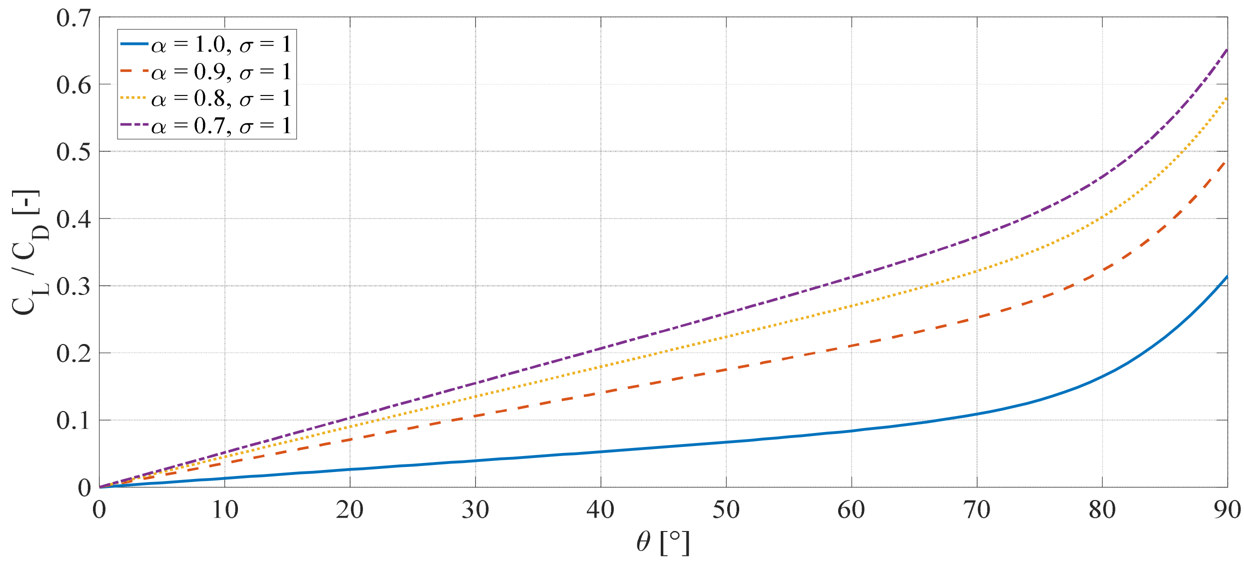

Fig. 6 Lift to drag ratio for a flat plate at different incidence angles θ and energy accommodation coefficients α calculated using Sentman's GSI model [102], which assumes diffuse reflection, at an altitude of 400 km and a wall temperature T_w of 300 K

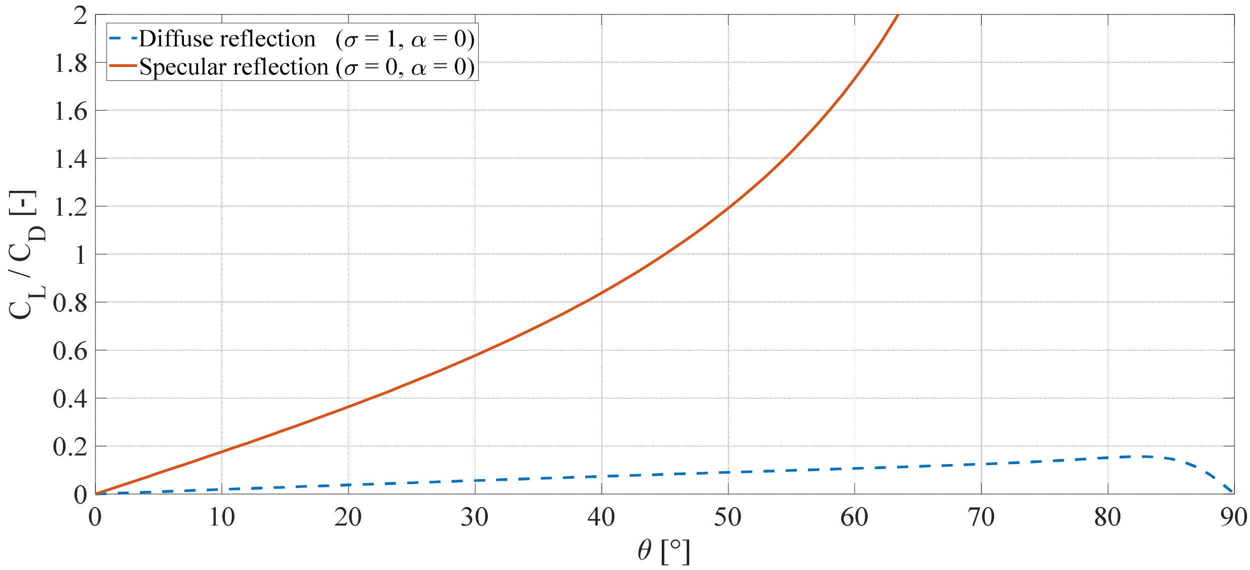

Fig. 7 Lift to drag ratio for a flat plate at different incidence angles θ calculated using a GSI model which assumes ideal ($\alpha = 0$, no energy transfer) and fully specular ($\sigma = 0$) or fully diffuse ($\sigma = 1$) reflection [106] at an altitude of 400 km

In addition, the surface erosion due to the collision with energetic and reactive particles, at VLEO primarily atomic oxygen, increases energy accommodation. Typical energy accommodation coefficients experienced in LEO are in the range 0.85 to 1.00 [101, 105].

Fig. 5 depicts how the lift and drag coefficients of a plate at different incidence angles θ ($\theta = 90° - \beta_i$) and at an altitude of 400 km and a wall temperature T_w of 300 K are affected by the accommodation coefficient according to *Sentman's GSI model* [102], which assumes diffuse reflection with varying degree of energy accommodation ($\sigma = 1$, $\alpha \neq 0$ and σ' dependent on α). Even though the drag coefficient moderately increases with decreasing energy accommodation coefficients (especially for low incidence angles), too, the increase in the lift coefficient is way more significant. Consequently, higher lift-to-drag ratios are achievable if energy accommodation can be reduced (see Fig. 6). To provide an upper limit of what could be feasible with advanced materials, Fig. 7 depicts the lift to drag ratio of a flat plate using a model which assumes ideal reflection ($\alpha = 0$, no energy transfer) for both fully specular ($\sigma = \sigma' = 0$) and fully diffuse ($\sigma = \sigma' = 1$) reflection [106]. For fully diffuse reflections the maximum lift to drag ratio is limited to $C_L/C_D < 0.2$. For fully specular reflections, though, lift to drag ratios $C_L/C_D > 2$ could be achieved [107].

So far only very little is known about how the flow incidence angle, the surface material or the surface roughness affects drag and lift. The limiting factor preventing research in this area has been the lack of experimental data. Material resistance to atomic oxygen has been an active research area with both on-ground and in-orbit tests being performed specially in polymers and composite materials ground [108–111]. However, as these investigations are focussing on accelerated material erosion testing, they are conducted using hyperthermal atomic oxygen sources at much higher flow rates, a carrier gas, or are pulsed, all of which changes the flow regime and the fundamental nature of the interaction with the surface for aerodynamics [97].

As a consequence, there exists a lack of campaigns to systematically obtain data from on-orbit experiments as well as a facility on the ground capable of reproducing and measuring the physical and chemical processes leading to observed behaviour and the flux distribution of the reemitted flow under relevant conditions [97].

Within DISCOVERER, a two-fold approach to eliminate this lack is followed:

Firstly, an entirely novel hyperthermal atomic oxygen wind tunnel, *Rarefied Orbital Aerodynamics Research Facility (ROAR)*, will be developed, built, commissioned and operated allowing the testing of materials in a representative flow environment [112]. ROAR is a dedicated apparatus designed to simulate the atmospheric flow in very low Earth orbits to investigate the impact different material properties have on gas-surface interactions, and determine the aerodynamic properties of materials from the reemitted gas distribution. To do so, the main characteristics observed in

VLEO, namely the free molecular flow regime and the flux of oxygen atoms at orbital velocities impinging on the spacecraft surface, have to be reproduced. This is accomplished by combining an ultra-high vacuum system with a hyper-thermal oxygen atoms generator. Materials performance will be assessed via a scattering experiment in which an atomic oxygen beam is incident on the surface of a test sample and the scattered species are recorded by mass spectrometers [112].

Secondly, a small test spacecraft, *Satellite for Orbital Aerodynamic Research (SOAR)* (Fig. 8) will be developed and flown to provide truth data for the ground-based experimental results [97, 113]. The principal scientific objective of SOAR is to investigate the variation of the aerodynamic coefficients of different materials and surface finish at different incidence angle to the oncoming flow and at different orbital altitudes.

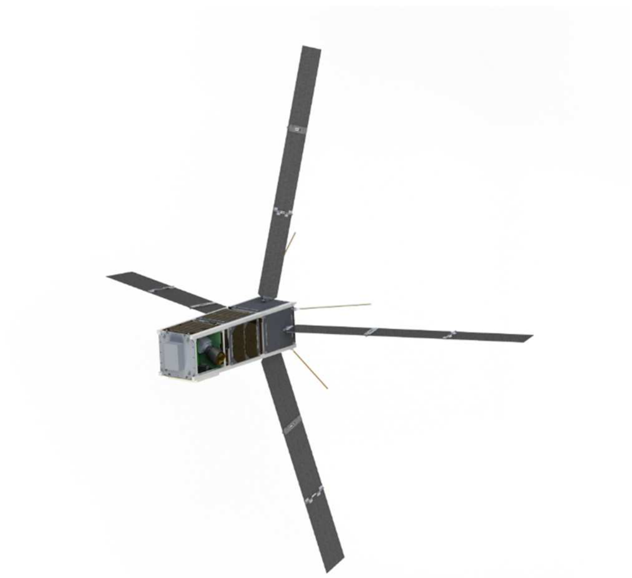

Fig. 8*:* Geometry and configuration of the SOAR satellite with steerable fins and INMS payloads [113]

In order to achieve these objectives, SOAR features two payloads:

1. A set of steerable fins which provide the ability to expose different materials or surface finishes to the oncoming ow with varying angle of incidence whilst also providing variable geometry to investigate aerostability and aerodynamic control.
2. An Ion and Neutral Mass Spectrometer (INMS) with Time-of-Flight capability which enables accurate measurement of the in-situ flow composition, density, and thermospheric wind velocity.

By providing in-situ density measurements of the oncoming flow which can be used directly in the recovery of the fitted aerodynamic coefficients and associated accommodation coefficients, this experimental methodology presents a significant advantage over previous observation based studies [113].

The expected increase in the magnitude of the available differential lift forces due to the application of enhanced surface materials would drastically increase the feasibility domain of differential lift and at the same time decrease the respective maneuver times. Thus, Smith et al.'s [27] statement according to which differential lift for the in-plane relative motion control of a rendezvous scenario is an inferior approach compared to differential drag needs to be re-evaluated for materials specifically optimized to create high lift-to-drag ratios. Besides the feasibility domain and the maneuver time, orbital decay needs to be considered as a third trade-off criteria. In addition, the interdependence of the available differential lift forces and the maneuver times for the out-of-plane relative motion control has not yet been analyzed at all.

3.2 Coping with uncertainties

A major challenge in exploiting environmental forces for satellite relative motion control is that exact values for the available drag and lift forces are hard predict. Both are functions of the atmospheric density, atmospheric winds, the velocity of the spacecraft relative to the medium, the spacecraft's geometry and surface properties, its attitude, its drag coefficient and its mass. The interdependence of some of these parameters (e.g. the drag / lift coefficients are affected by the temperature of the medium which also influences its density) and the lack of knowledge in some of their dynamics make the controller design and the design of realistic guidance trajectories a challenging problem [49].

Linearized models along with a constant density assumption are valuable tools for developing analytic trajectories, to gain deeper insights or to design simple reference trajectories. However, open loop controls developed using this practice are unlikely to fulfill their purpose in a real mission scenario. As revealed in the presented literature review, this applies to all rendezvous control methodologies using differential lift proposed so far [20, 26]. Also, the robustness of the controller for formation keeping purposes developed in [89] is questionable since it assumes constant and a priori environmental conditions, too. Consequently, modifications should be made to adopt viable strategies that are invariant to disturbances and uncertainties. In the field of differential drag, effort was done by several researchers to develop robust control strategies using advanced control principles able to cope with the occurring uncertainties such as:

- *Lyapunov Control*
- *Sliding Mode Control (SMC)*
- *Model Predictive Control (MPC)*

They can function as a guiding principle for the controller developments in the field of differential lift, for which no robust control methods exist so far at all.

A second difficulty is the design of realistic guidance trajectories. Uncertainties in the atmospheric density forecast result in errors in the guidance trajectories, and vice versa, any improvement in the atmospheric density forecast will allow to calculate more realistic guidance trajectories. Frequently used global atmospheric models are often designed to calculate more than just a specific parameter (such as the density) leading to higher computation time and less accurate results for the specific quantity [114, 115]. A critical assessment of atmospheric modelling can be found in [62]. This can be circumvented by using a localized models, originally proposed by Stastny [116] for density prediction, limited to predict one specific parameter along the orbit of a certain spacecraft. Thereby, the accuracy of the results can greatly be enhanced [114, 115]. A similar approach was developed by Pérez et al [114, 115] to predict the density along the orbit. However, instead of a linear model, *artificial neural networks* were used. Even more realistic results can be obtained using a method denoted as *spatiotemporal resolution* developed by Guglielmo et al. [64], which reflects the dependence of the density on both spatial and temporal differences [64, 117]: "*Spatiotemporal resolution can be achieved by propagating multiple orbits of spacecraft using a density forecast/estimate, varying the ballistic coefficient for each one. The density-location pairs result in the creation of a density field. The latter can be obtained on the ground prior to the maneuver, and uploaded at an opportune time. Interpolating the uploaded density field allows the creation of a relative guidance trajectory*" [64].

The just discussed methods, originally developed in the course of differential drag, provide valuable insights into the problematic related to the creation of guidance trajectories, which similarly occur in the field of differential lift, too, and should be taken into account in future developments.

4 Conclusion

Using several small, unconnected, co-orbiting satellites rather than a single monolithic satellite strongly enhances the robustness, flexibility and redundancy of satellite missions. However, due to their tight volume and mass constrains other solutions than using chemical thrusters to withstand given natural perturbations and/or to perform reconfiguration maneuvers are of highest interest. In VLEO as well as low LEO, atmospheric forces are a possible solution for propellant-less relative motion control.

After giving an introduction into the topic, this paper presents an extensive literature review on the developments in the field of differential drag as well as a combined approach of differential lift and drag. Since lift acts perpendicular to drag, the latter offers the unique possibility to propellant-less control both in-plane as well as out-of-plane relative motion and in addition to mitigate the orbital decay caused by the control actions. While differential drag is thoroughly developed and even proven to be successful in reality, using differential lift and drag is only poorly studied. Based on these insights, several key knowledge gaps that need to be addressed in order to enhance the current state-of-the-art are revealed.

A main gap is the analysis of the interdependence of the feasibility domain of differential lift controlled maneuvers (e.g. the maximum separation distance or the maximum maneuver altitude) and the achievable lift-to-drag ratios. Despite its potential, differential lift is currently the inferior option due to its lower control authority. However, research efforts conducted in the course of the DISCOVERER project aim to develop materials which encourage specular or quasi-specular reflection. It is expected that the application of the developed materials will provide higher lift-to-drag ratios so that the so far performed analysis needs to be re-evaluated. Increased available lift forces drastically enhance not only the feasibility domain of differential lift but also the respective maneuver times. An interdependence of the respective parameters, however, has not been analyzed at all.

In addition, the robustness of the control strategies proposed up to now is questionable: when using aerodynamic forces for the control of satellite formation flight, control strategies which are invariant to disturbances and uncertainties are required. Promising examples from the field of differential drag were summarized and can function as guidance principles for future developments. Once the control theory for all use cases is developed, an extension of the method to an arbitrary number of satellites as well as collision avoidance strategies will help to advance the state-of-the art and to make the methodology a suitable option for real mission scenarios.

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