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Orbital Observation of Dust Circulation Phenomena on Airless Celestial Objects as a Tool to Characterize Areas of Interest for Landing

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***Abstract*— Electro Optical (EO) sensors are almost ubiquitous on man-made space platforms, where they are used to carry out measurements, observations, and Guidance, Navigation and Control functions. This study, specifically, looks at a speculative way of using EO sensors' measurements to recognize regions which a surface element operating on a celestial object would find critical during and after landing. Highly resistive rocky astronomical bodies lacking an atmosphere can develop, on their outermost layer, a complex plasma environment and electrostatic fields. This happens due to the coupling and interaction between solar activity and the object's surface. In these fields, charged regoliths grains can, after departing the surface, move due to acceleration by gravitational and electrical forces. Regoliths flowing through the plasma can be regarded as a set of tracer particles; consequently their motion can, in theory, be analyzed using flow tracking techniques, corrected to take into account the motion of the orbital platform carrying the tracking sensor. The zones where over time these particles would tend to settle down might represent areas of interest for a landing mission. The implication is related to their association with areas causing mobility, perception or energetic issues, which would become evident as sink flows, areas attracting mass flow. Therefore, remotely measuring the direction of this flow employing EO sensors (this capability, for example, could be provided by Doppler LiDARs) would potentially provide a robust way to detect optimal landing zones over the surface of the celestial object.**

Keywords—Doppler LiDAR, Dust Levitation, Remote Sensing, Space Landing, Hazard Detection

I. INTRODUCTION

On the 10th of January 1992 the vessel Ever Laurel was hit by a storm while sailing in the Northern part of the Pacific Ocean. As a consequence, a dozen containers carried by the ship slipped overboard. One of these was housing a shipment of thousands of colourful floating bath toys, shaped like ducks, turtles, frogs, and beavers. It might sound unlikely, but this event ended up revolutionizing the study of the oceans. The oceanographer Curtis Ebbesmeyer and his colleagues [1] for almost two decades tracked the path of these objects, which ended up washing ashore on the coasts of places ranging from Oceania to South America, up to the United Kingdom. They used them as impromptu tracer particles seeded into ocean currents, to (successfully) improve the accuracy of circulation models.

Let us now suppose we are living on a planet where the ocean is constantly generating colourful bath toys. On this planet we want to solve the inverse problem: there is a well-established body of knowledge regarding the currents, but data about the coast lines are lacking.

Tracking the floating toys for a time $t^T = T^C \Omega$, with Ω a scaling factor such that $\Omega >> 1$ and T^C the average characteristic time necessary for a toy to move from the point where it is produced to the point of capture, would allow generating a coarse outline of the global landmass profile. Through a sustained processes of milling (comminution) and aggregation (agglutination) [2], a layer of loose material is continuously produced on the surface of airless bodies. This loose material, in a similar way to how ducks settle on the contour of landmasses, generally tends to settle down in areas with peculiar topological properties, which, incidentally, are of special interest for a landing object.

The scope of this paper is to present a heuristic strategy to be used to determine zones of intrinsic interest for a spacecraft that is required to autonomously choose a landing spot on an airless, rocky, celestial object, using observations of the local behaviour of dust particles. This could be seen as a peculiar application of sensors, employing an optic based approach to automatically provide an emerging smart decision. Whilst it is hard to envision it as a primary decision system, as it makes use of a phenomenon which might be absent or weak in some places, it might nevertheless represent an useful ancillary routine providing an additional lever for autonomous decision making.

II. DUST LEVITATION ON AIRLESS BODIES

Rocky astronomical objects devoid of a dense external gaseous layer and characterized by the absence of magnetospheres - either internally generated or induced, the latter being the case, for example, for Saturn's moon Titan [3] abound in the Solar System. Around these celestial bodies there is no known physical mechanism capable of trapping, absorbing or dispersing the bulk of the flux of charged particles and radiations flowing from the Sun. Tidal forces, mechanical and chemical transformations due to thermal effects in proximity to the Sun, and impacts not mitigated by an atmosphere all lead to the generation of nano- or micro-metric scale grains. These particles then interact with superficial electrostatic fields; this interaction can then lead them to be levitated and transported around the surface.

It is beyond the scope of this paper to provide an exhaustive explanation of the physics behind this phenomenon; additionally, even though electrostatic dust levitation has appeared in the scientific literature almost half a century ago [4], according to Szalay et al. [5], a comprehensive explanation of this process is still an open question.

While the way in which these grains are winnowed from the surface is still not fully understood, there appears to be consensus on their fate once they enter the transport process. According to Lee [6]: "*Larger levitated particles remaining gravitationally bound to the asteroid* ($\geq$ 1– 100 μm) *are redistributed across its surface following local electrostatic and gravity gradients. Their migration is arrested when they settle in topographic traps and/or in perennially shadowed areas (e.g., craters, grooves).* " and "*(...) Still larger particles levitated at subescape velocities experience lateral transport along local electrostatic and gravity gradients, and accumulate in topographically sheltered areas and/or in lows in dynamic height.*".

This is further corroborated by Poppe et al. [section 3.2 [7]], where using a Particle-In-Cell simulation the authors are able to demonstrate that on the dayside of the Moon a surface feature – a crater – persistently acts as an attractor and trap for levitated particles. These features appear to be extremely effective at confining larger speckles, with the larger particles being less likely to escape the topographic feature. The above mentioned paper presents both temporal and spatial scales for this phenomenon, and outlines how the behaviour of regolith grains varies in proportion with their size. All this information is extremely important for the selection and calibration of an appropriate remote sensing instrument.

Interestingly, Piquette and Horányi [8] expanded the results of Poppe [7] by including a feature on terrain leading to an asymmetric scenario, discovering that the weaker the gravitational attraction of the celestial object, the more enhanced the features' or relief-induced shadows' attraction is.

III. The Method

No standard framework for the autonomous intelligent selection of a landing site for an aerial robot seems to exist, to date, within the scope of reviewed literature. That said, it is not odd to imagine this artificial intelligence represented as a collection of $m, m \in \mathbb{N}$, expert subsystems, each negotiating a compromise between different motion scenarios, such as moving towards or avoiding a particular zone. Each of the subsystems would promote a certain behaviour depending on its scope, which might, for example, be reaching areas of scientific or economic interest, protecting the probe against a specific hazard, finding suitable zones to initiate the construction of low-g factories or outposts, and so on.

The strength with which each of these "pulls" happen can be seen as a weight in a mathematical model. The final decision, (0th operative level), can be seen as a function $\hbar(\underline{w})$of the m weights (the 1st operative level) with each of them in turn being a function of another set of weights: $w_i, i = 1, \ldots, m : w_i = g(\underline{v}^i)$, belonging to a 2nd operative level. The methodology described in this paper belongs to the most (almost exclusively) studied class of first level objects, that of hazard detection. Usually, the process of detecting threats is coupled with the task of avoiding them (HDA, Hazard Detection & Avoidance). Avoidance is, however, only one of the possible actions to be taken once the ultimate decision has been made. More specifically, the method described in this section is a possible way to estimate a second-level weight for a first-level subroutine tasked with detecting external features putting the surface element of the mission in danger; an example on how the hazard detection problem is currently addressed might be seen in Cui et al. [9].

All the activities which require an interaction with a human-related activity might easily be associated to standardized fiducial markers to be used in a cooperative approach. Scouting or prospecting unknown areas in search of natural resources or features, on the other hand, requires an elevated degree of robustness and flexibility: therefore is imperative for the probe to be capable of adapting to and understanding as many external cues as possible.

Let us suppose that the spacecraft carrying out the mission is composed of two elements, an orbiter and a lander; or simply an orbiter capable of landing. Additionally, in both cases the landing capacity is assumed to be completely autonomous, relying solely on the spacecraft's decisional ability. A lander is trivially present because part of the mission objective is landing, whereas the presence of an orbiting element is part a broad variety of possible mission architectures. It is through the orbiter that remote sensing, and therefore, effectively, the search for zones which might pose a threat for a surface element is performed. These areas, for example, may be consistently shadowed zones, where solar panels might not be able to collect enough energy or topological depressions, which might be difficult to move away from.

The last hypothesis is that the lander is capable of generating a suitably high-resolution three-dimensional model of the celestial object and to consistently position the observed features, as well as its own position on this map (Simultaneous Localisation and Mapping).

The injection of a regolith particle into a $(R^0, \theta^0, \varphi^0)$ point of the plasma layer surrounding the asteroid can be seen as the extraction of a random triad of numbers, which then acts as the seed for a stochastic gradient descent algorithm over a three-dimensional manifold which is the asteroid topology itself, its minima coincident with points critical for surface operations.

Since this process is likely to be extremely perturbed by external factors, and noisy, only tracking a sufficiently high number of particles over a consistent time would give the ability to correlate an observed convergence to a process like the one described in the previous section. To a degree, this could be interpreted as if the probe would be observing a Monte Carlo simulation of the pseudo-gradient descent process.

The information of interest is therefore the local direction of the particle circulation. At the current technological level, it is impossible to continuously track the position of single grains for a sufficient time. This stems from the difficulty to identify and track each specific particle for a finite time interval. It is possible, however, to exploit a property known from kinematics, namely one related to the direction of the instantaneous velocity of an object. Under the limit of a time interval going to zero, the average velocity vector, is, at any given moment, tangent to the trajectory of the object itself. Hence, thanks to their 3D sensing and mapping capabilities, remote sensing EO sensors seem to be the best tools to represent the instantaneous velocities of floating regolith grains into a 3-dimensional vector field distributed over the shape of the celestial object.

This vector field, representing instantaneous velocities, would be sensitive to a multitude of random factors. However, given the behaviour outlined in Section 2 it is possible to state that areas of the field which over time consistently act as attractors or sinks are most likely areas of interest for a landing object.

Since the upper boundary of the transport scale is the order of magnitude of the Debye length of the surface plasma, λ, to detect the features of interest in the velocity field a possible strategy is to divide the asteroid surface into patches with a characteristic scale of σ, $\sigma = \lambda/K$, for simplicity $K \in \mathbb{N} : K > 1$, and count over time which are the patches towards which most of the vectors representing velocities converge.

IV. POSSIBLE TECHNOLOGICAL SOLUTIONS

The methodology described above could hardly rely on a dense network of surface sensors, since the transport phenomena are strongly local. This results from the local plasma structure being of the order of magnitude of the Debye length; therefore that kind of implementation would require a way too large number of evenly distributed particle velocimeters to be cost effective and realistically feasible. However, there might still be possible surface applications: for example, it could be employed in navigation system for rovers, controlled to move "upwind" with respect to the regolith stream so as to avoid getting stuck around obstacles or zones where the solar panels would not be able to generate enough power.

Continuing to address this idea as being based on the use of orbital remote sensing it is natural to treat the engineering side of this problem as finding the optimal electro-optical sensor capable of registering the phenomenon within an acceptable level of accuracy, given all the constraints typical of the space environment.

The most similar existing application is remote sensing of atmospheric particulate matter, with the difference that in that case the sensor is trying to detect an aerosol, which by definition is made of solid or liquid particles dispersed in a gas. Therefore, all the techniques based on using differential analyses between the gaseous and the dispersed phase, or analysing the scattering of atmospheric molecules (the appropriate scattering theory depending on the operative wavelength of the instrument and the atmospheric composition) cannot be used in this context.

Attempting to obtain the vector field of motion through three dimensional Particle Image Velocimetry, possibly achieved through a pair of coupled orbiters, with one of them providing active illumination, and the other observing seems exaggeratedly complex for the benefit that the information might provide. Other phenomena sometimes used in imaging, are the ones related to polarization. These, however do not seem to be critical, or interesting for the sensing scope, given the scale and the order of magnitude of the flows and fields at play.

Thus the most suitable sensor, appears to be Doppler LiDAR [10], [11]. In particular, given the usual regolith size and the wavelength used for sensing, the channel exploiting the signal derived from Mie scattering. For instance, in August 2018 ESA launched the Aeolus satellite, equipped with a sensor named ALADIN, capable of determining the global wind flow distribution – its scope being similar to the one outlined in the introduction for Oceanic currents. ALADIN achieves this using an UV Doppler LiDAR tracking particles below the spacecraft, both if the sky below the instrument is clear, in which case Rayleigh scattering of the atmospheric molecules is read, or if the sky is cluttered with aerosols, which are registered through the Mie scattering channel [12], a technique not dissimilar from the one proposed in this paper, used, however, for a completely different purpose.

Given the lack of a backup channel, like the Rayleigh one could be, if the levitating regoliths density is estimated to be generally too low to provide an adequate level of information, the information intrinsically present in the fields might be artificially augmented to be harnessed. This, for example, could be accomplished by dispersing electrostatically levitatable floaters. Also of interest could be the use of von Neumann machines-like in-situ dust generators and injectors.

The design of floaters should be seen as an optimization problem between various trade-offs, constrained so as to have the highest possible surface to weight ratio, an elevated visibility with respect to the wavelength of the sensor, and a low volumetric footprint for storing reasons, which could possibly be achieved through genetic algorithms. The weight constraint is important not only from a dynamics point of view, so as to allow them to easily win gravitational pull, allowing even weak electrostatic fields to provide information, but must be enforced also to reduce the impact on the spacecraft mass budget, which is critical. The volumetric constraints might be addressed with dynamic origami-like objects, capable of unfolding upon impact to greatly increase their surface.

V. CONCLUSIONS

This paper presents a conjectural strategy to determine, from an orbital platform, topologically critical zones for a landing probe. This speculative approach operates by simply measuring the spatial evolution over time of a naturally occurring process. Since at the moment there are no data to corroborate or falsify this hypothetical methodology, further work is required to test the feasibility and the usefulness of this method. If demonstrated valid, however, it could both be useful in projects of wide-ranging unmanned exploration and exploitation of the Solar System, and stimulate research in a broad variety of related fields, with possible benefits both for terrestrial and space applications.

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Monitoring dust motion around airless celestial bodies: characterizing suitable landing zones

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