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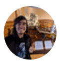

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Abstract—**Autonomous mission planning for unmanned aerial vehicles (UAVs) aims to leverage the capabilities of UAVs equipped with on-board sensors to accomplish a wide range of applications, including planetary exploration where greater science yields can be achieved at lower costs over shorter time periods. A significant body of research has already been performed with the aim of improving the autonomy of UAV missions, particularly in the areas of navigation and target identification. In this work, we review current approaches to drone navigation and exploration for planetary missions, with a focus on Mars and the main autonomy levels/techniques employed to achieve these levels. Recognising the importance of astrobiology in Mars exploration, we highlight progress in the area of autonomous biosignature detection capabilities trialed on Earth, and discuss the objectives and challenges in relation to future mission to Mars. Finally, we indicate currently available software tools and future work to improve autonomous mission planning capabilities.**

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1. Introduction

The exploration of our solar system is of increasing interest to space agencies and private enterprise, with more players involved thanks to the increasing capability of space-based technology and the reduction of costs. The use of landers, rovers and balloons has been explored, but these devices typically cover small areas of the target bodies, limiting contextual information that is crucial for astrogeological and astrobiological investigations [1].

The use of UAVs, also commonly known as drones, has been proposed to expand and complement the capabilities of rovers and landers for planetary exploration. Drones could survey and find geological features at a higher resolution than orbiters, and cover wider areas than rovers [2]. A number of missions have been considered using fixed-wing, flapping or nature-inspired, and rotary-wing UAVs [3].

The most optimal locations in the solar system to fly a drone in terms of atmospheric temperature ranges, density, gravity and winds, are Venus, Mars, Titan and Triton [4]. NASA currently has plans to explore these environments in the future with UAVs. The Mars Helicopter, for example, is scheduled for departure towards Mars in July 2020 attached to Mars 2020 rover belly (Figure 1), and the Dragonfly [5] has been selected to be launched in 2026 and arrive Titan in 2034 [6].

Figure 1. **Mars Helicopter attached to Mars 2020 Rover [7]. Image credit NASA/JPL-Caltech.**

In this review, we focus on robust decision making and mission planning, an area that improves the sensing, interpreting, and reacting/actin capability to unexpected environmental changes or findings. The main objective of mission planning for biosignature detection is to make the best decisions available using a decision-making model, looking at the optimal way to explore (Mars) and get the best reward (Inspection/Images of best biosignatures candidates places) at a lower risk.

Biosignature detection still being a challenge to tame on Earth and Mars. Different techniques are used today to detect biosignatures at different scales, the more important techniques and more relevant to planetary exploration are presented. New approaches to detect organic material inside stromatolites exhibit positive result for the preservation of life trails on Earth. Also, Mars will be scrutiny by

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new instruments such as PIXL (Planetary Instrument for X-ray Lithochemistry) and SHERLOC (Scanning Habitable Environments with Raman Luminescence for Organics and Chemicals). These instruments aim to map mineralogical and elemental composition in situ at microscopic scales [8].

This paper is organised as follows: Section 2 covers the main details related to Mars exploration using drones and presents a summary of drones designs for this purpose. Section 3 makes a consensus of the UAV autonomy, highlighting the main parts and the desired level of autonomy required to conduct autonomous planetary exploration. Also, are presented some techniques available such as MDP and POMDP to deal with navigation and mission planning of UAVs. Section 4 introduces the biosignatures general facts, the importance and context of this detection with life hunting and the techniques used to detect it on Earth and the most related work on Mars. Future work is presented in Section 5, and Section 6 provides conclusions.

2. PLANETARY EXPLORATION USING DRONES

Planetary exploration faces several problems that eliminate the option of real-time mission planning from Earth. Round-trip light travel time between Earth and Mars can be more than 20 minutes and for Titan almost 3 hours [9]. These problems namely light-time latency and line-of-sight between other planets and Earth are caused by long interplanetary distances and orbital motions of the planets. Another problem is the increasing amount of data that can be collected due to the growing capabilities of instruments, this data must be processed and reduced before sending it back to Earth. This is known as data-limited mission planning and leads to significant time cost for the mission execution [10].

The light-time latency problem is a law of physics restriction. Line-of-sight and data transmission-rate are problems that can be partially solved, sending more capable communication vehicles or increasing the autonomy of the system to explore and determine the best data to be sent back to Earth [10].

The UAV ability to move over the surface and through the atmosphere, enhance the cost-effectiveness and efficiency compared to actual wheeled or static explorers in planetary exploration applications [11].

The main intended applications of UAVs in Space are surface exploration, surface characterization, determination of potential rover paths, identification of possible human landing sites and finding hazards in advance. Also, UAVs can help astronauts in the future providing autonomous reconnaissance. Other possible activities are geographical mapping, atmospheric composition and characterization, soil composition analysis, surface thermal characterization, and magnetic field measurement [4].

In the design of UAV for Mars and Titan must be addressed phases such as space transit, planet entry, deployment, and stabilization [11]. Hassanalian, *et al* [4] consolidated and discussed UAV research for space exploration before 2017. The authors, however, concentrate on the design features and not on autonomy, navigation or mission planning. Table 2 presents to the best of our knowledge, all peer-review literature for UAV on Mars and Titan conducted after 2008 focused on autonomy, navigation and mission planning details.

The main categories for UAVs are fixed-wing, rotary-wing, VTOL (Vertical Take-Off and Landing) and flapping wings [4]. Multiple types of designs are available but without further specifications [12] such as extreme Access Flyers [13], Mars hoppers that use CO2 to fly [14], Mars Electric Flyer concepts [15], Mars airplanes [16], Titan aerial platforms [17], [18] and manned recognizance airplanes for Mars [19].

The atmosphere of Mars imposes important restrictions on drone design. Parameters such as weight, speed of the aerofoil, and the payload size and weight must be carefully balanced in order to improve flight endurance and mission performance/capability [2].

The Exploration of Mars with UAVs will open a new frontier in exploration. Mars surface has been radiated given the low density of its atmosphere, this potentially has destroyed organic compounds in the surface related to the organic process in the Mars past [20]. Places like caves and cliffs will extend the knowledge, complementing the surface data. The exploration of less radiated places under the surface or in natural geological faults has the potential to foster the search for life on Mars.

Mars Environment Restrictions

Mars is the best-known planet after Earth [21] with significant atmosphere and water [22]. Current research aims to find remains of life on this planet, given the possibility of preservation of ancient life [23]. Mars is a cold planet, with a wide range of places in which possible ancient life may have left biosignatures. For landers or rovers who cover small areas moving slowly over the rugged surface, the problem of finding biosignatures is challenging.

A Martian day named SOL is slightly longer (about 39 minutes and 35 seconds) than Earth day [24]. Temperatures over the surface vary from lows as -140 °C during winters and up to 20 °C in summer. Surface pressure varies between 0.4-0.87 KPa. The Martian atmosphere is only around 1% of Earth's atmosphere and is composed mainly of carbon dioxide, with some nitrogen, argon and a small concentration of water and oxygen. Most relevant details about the Martian atmosphere are presented in Table 1. Atmosphere on Earth over 30Km is similar to the Mars atmosphere [4].

Table 1. Comparison of Earth and Mars Parameters adapted from [25], [26], [27], [28], [29] and [30].

	Earth at Sea Level	Earth Stratosphere ($\approx 30km$)	Mars
Gravity (m/s^2)	9.81	9.715	3.71
Atmospheric Composition	N2 - 78.08% O2 - 20.95% H2O - 0-4% Ar - 0.93% CO2 - 0.036%	CO2 - (ppm) H2O - (ppm) O3 - (ppm) N2O - (ppb)	CO2 - 95.32% N2 - 2.7% Ar - 1.6% O2 - 0.13% CO - 0.08%
Atmospheric Density (kg/m^3)	1.225	0.01814	0.0138
Average Temperature (K))	288.15	226.51	210.15
Average Wind Speeds (m/s)	0-100	0-60	2-7 (summer), 5-10 (fall), 17-30 (dust storm)
Speed of Sound (m/s)	340.3	301.8	245
Dynamic Viscosity (Ns/m^2)	1.789×10^{-5}	1.475×10^{-5}	1.2235×10^{-4}

Orbiters such as the Mars Reconnaissance Orbiter (MRO) [43], landers as Insight [44], and rovers [45] such as Curiosity [46] have brought us information about Mars and its history.

Table 2. Space Drones since 2008

Name	Year	Target Body	Kind of Drone	Range (Km)	Endu-rance (m)	Mass (kg)	Mission type	Power supply	Autonomy proposed	Navigation strategy	Mission planning	Ref
ExoFly - DelFly 2	2008	Mars	Flapping-wing	10	12	0.02	Scouting terrain to aid in path planning	Solar	Autonomy on external rover	Vision based	-	[31] [32]
Mars Airplane	2009	Mars	Fixed-wing	-	-	-	-	-	-	-	-	[33]
-	2011	Mars	Coaxial Rotary-wing	-	-	33.12	-	-	-	-	-	[4]
Gas Hopper	2012	Mars	Ballistic hopper Fixed-wing	100 /hop	-	-	Finding water on Martian subsurface using (GPR) ground penetrating radar	Solar	-	-	-	[34]
MASSIVA, Halcyon, Hyperion, Y4TR	2013 - 2016	Mars	Fixed-wing Coaxial tilt rotor VTOL	1000	60	25	Explore the surface	Solar	-	-	-	[26]
Mars helicopter	2014 - now	Mars	Coaxial Rotary-wing	-	1.5	1.8	Technology demonstration, scouting platform	Solar	Autonomous flight	downward looking camera	Commands from Ground	[35] [36] [37] [38]
Prandtl-m	2015	Mars	Fixed-wing	32.1	10	12.7	-	-	-	-	-	[39]
6Xsol6	2016	Mars	Hexacopter Rotary-wing	-	28	6.5	Acquire data of Mars atmosphere and surface	Solar	-	Point based	Pre planned point based	[40]
Mars airplane	2016	Mars	Fixed-wing	300	-	3.07	Observe the Martian magnetic field and take close-up pictures	-	-	-	-	[41]
Marsbee	2017	Mars	Flapping-wing Bumblebee inspired	-	-	2.14 x10^{-4}	-	-	-	-	-	[42]
Dragonfly	2016 - now	Titan	Octocopter Rotary-wing	60	120	300	Explore surface and atmosphere in search of a chemistry that could foster life	Radio-active generator	-	Optical Navigation	-	[5] [6]

- Not available or not provided

One of the remarkable findings is the chemical ingredients of life [47]. Mars atmosphere and surface are well-known, nevertheless what is know is limited given the magnitude of the exploration task and the limitation of the current vehicles. NASA has plans to use UAVs to explore Mars faster. The Mars 2020 Mission will test a Mars helicopter [37] as the first UAV heavier than air (not a balloon) in another planet's atmosphere.

Communication challenges— The communication with the orbiters, rovers and landers on Mars are possible through the Deep Space Network (DSN) [48]. DSN is composed by a network of big antennas (spaced approximately 120°) over the world, one in Goldstone near California in the USA, other near Madrid in Spain and one near Canberra in Australia. This antennas (70 meters and 34 meters dishes) can communicate with the Mars Curiosity rover directly (slowly) or through the Mars Reconnaissance Orbiter (MRO) (higher speed, and line-of-sight available almost 16 hours each day) [49].

The data rates range from 2 kb/s to 2048 kb/s, using different band spectrums, such as S (2090-2118MHz), X (7145-7190MHz) and Ka (34315-34415MHz) bands [50]. This communication conditions limits the amount of data that can send and receive from the vehicle Curiosity rover. This problem will increase with the number of active missions using those communication channels, for example, the new Mars 2020 rover have 23 cameras, 9 for engineering, 7 for science, and 7 for landing, it entails that a big amount of data will be generated and must be scheduled to send back to earth [51].

3. UAV Autonomous Mission Planning

UAV mission planning involves multiple activities including take-off, initialize state estimator, collect sensor data relate to mission plan and land, also checking the battery voltage and motor nominal performance during the flight [52]. In case of having a fixed charging ground station, the UAV required to return to the vicinity of the station before landing maneuver execution, this maneuver include finding the landing site using vision. After landing, the battery charging and data download process begin [53]. Is suggested to run during the entire process a system health observer to monitor all critical components [54].

The desired level of autonomy for a planetary exploration autonomous mission planning is called science autonomy. This level of autonomy computes a mission plan based on the analysis and interpretation of data collected. This level of autonomy run over the fully autonomous system (Hardware), selecting the best places to collect data, analysing which data fits better the science goals and is more valuable to be sent back to Earth [10].

UAV Autonomy

Autonomy is associated to a system that use their own capacities to manage their interactions with the environment, entirely self-regulating and self-governing, taking actions that best benefits their own requirements, defining goals and objectives without outside instructions. One important criterion to assess the autonomy of a system is how well it carries out an associated task without operator involvement [55].

High levels of autonomy do not mean that the system can not receive instructions from experts, it means that at a certain level, the system does not require external monitoring or supervision to accomplish the mission assigned. Though autonomous system requires to have continuous monitoring of its own resources, tasks priorities and mission risks [56].

UAV autonomy refers to operations in the field, without humans in the loop (human intervention), performing new or repeated flights for long-term missions. For autonomous flights on other planets is essential to have fully autonomous hardware, it includes automatic recharging systems, precision landing (in case of having a recharge station) and a high-level autonomous decision making, to follow a given mission [53].

Several approaches have been proposed for measuring the autonomy of a UAV system [55]. These include the draper three-dimensional Intelligence space [57], the Autonomous Control Level Chart (ACL) [56] with 9 levels from 0 (radio-controlled UAV) to 9 (fully autonomous system), the Sheridan scale for autonomy [58] and the Veres scale [59].

Three main general levels of autonomy can be extracted from these approaches: 1) Human-operated, in which an expert operator takes all the decisions, 2) Semi-autonomous, were the system has the capacity to do path planning, collision avoidance and autonomous departure/return, but the operator can interrupt when the vehicle is unable to perform its assigned tasks, and 3) Fully autonomous, in which the UAV locate its position, generate its trajectories, and only require prior knowledge about the environment, candidate golds and hazards to execute the mission [55].

The main levels of autonomy identified in the literature including the science autonomy are presented in Table 3, this table includes software and hardware technologies required to accomplish those levels.

Table 3. Autonomy levels identified and adapted from [55].

Level of Autonomy	Software Requirements	Hardware Requirements
Science autonomy	Autonomous mission planning	Science instruments
Long-duration autonomy	Recharge procedures	Automatic battery recharge system
3) Fully autonomous	Mission planning and execution Target finding	Sensor for mission (Camera) Sensors for target finding
2) Semi-autonomous	Simultaneous Localization And Mapping (SLAM) Collision avoidance Path following Path planning Autonomous departure/return	Enhance Perception (Camera/Lidar) Perception capability Odometry Onboard computer AutoPilot
1) Human-operated	Flight controller Motor velocity control	Radio control Flight capability Structure

An autonomous UAV system can and has been archived on Earth using State-Of-The-Art Hardware (UAV structure, flight systems, payload, storage and ways to replenish energy), control subsystems (for motor speed computation and trajectory tracking) and guidance (navigate and follow a mission) [53].

There is no GPS on Mars, therefore, one requirement is to have vision-based landing using a downward-facing monocular camera. This has been well studied using AprilTag visual fiducial markers [60], this solution is presented as the more lightweight and power-efficient. Also, there are several landing approaches using labelled and unlabeled landing sites. The robustness of the label landing algorithm is a trade-off of the robustness in the non-label landing sites [53]. Other tools such as semi-direct visual odometry (SVO) must be used to navigate and estimate motion from a downfacing monocular camera [61].

The long-duration autonomy needed for planetary exploration, however, requires a capability to recharge the batteries without humans in the loop [62]. Battery recharge process can be done by two main ways, using some hardware to transfer power to the UAV from a system on ground [53] or having a power source onboard such as solar panels attached to the UAV [37].

There are different options for UAV autonomous charging including wireless charging [63], contact-based charging pads [37], battery swap systems [64], solar panels [36] and Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) [5]. Wireless is the easier solution to implement with UAVs, but this requires to land on a charging station, limiting the range of the UAV.

Wireless charging takes more time than contact-based chargers or battery swap systems but is less complex and easy to maintain [53]. Radioisotope Thermoelectric Generator is only suitable for big and heavy UAVs in places with dense atmospheres and low gravity such as Titan, given the high weight of the Generator. Solar panels are complex to implement but free the UAV on having to land at a specific site making possible to cover wide areas.

UAV Navigation

Navigation is the process in which a path is defined and followed between two positions [65]. The steps involved in navigating include the definition of a path and the following of that path. There are several approaches for UAV navigation, which can use path planning techniques such as graph-based, sampling-based, potential fields, optimization-based, swarm-optimization and learning-based [66].

Path planning techniques can be combined with path-following methods such as Carrot Chasing, NonLinear Guidance Law (NLGL) or Lyapunov functions, pure Pursuit and Line-Of-Sight (PLOS), based on vector fields, based on Linear Quadratic Regulators (LQR), Model-based Predictive Controllers (MPC) and Surface intersection [66].

Autonomous navigation requires a collision-avoidance strategy, some approaches are artificial potential field, vector fields histograms, dynamic window approach, velocity obstacles, path deformation, fuzzy logic, bio-inspired approaches [66].

Most navigation techniques are not robust to be used in probabilistic environments, with uncertainty in the measurement and the environment [67].

UAV Mission Planning

UAVs can benefit from similar mission planning and navigation approaches used on rovers. An autonomous software running on Curiosity rover, for example, was designed to make use of dead times in the cyclical mission operations process [1] (figure 2). The software autonomously collects data of the surrounding environment for the Mars Rover Curiosity team that helps to plan the next sol mission. This cycle is composed of 6 steps [10], during the expert analysis and planning step on Earth, the rover can be on dead time waiting for communication windows or for instructions to execute.

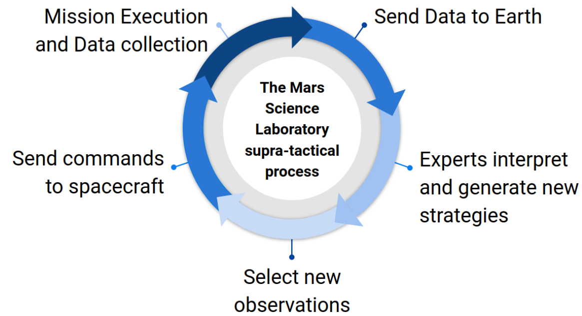


Figure 2. The Curiosity Rover Mission Operation Process adapted from [4] and [10]

A tool from NASA called Autonomous Exploration for Gathering Increased Science (AEGIS) where developed to make use of this dead time [1]. This software was developed as part of a larger autonomous science framework called OASIS (Onboard Autonomous Science Investigation System) [68]. AEGIS does autonomous target selection and data acquisition, increasing the exploration performance from 24% to 93% , selecting the most desired target material without Earth scientist in the loop. The software uses the rovers navigation cameras as input and suggests targets to the remote geochemical spectrometer instrument or ChemCam [55]. AEGIS looks into the images for features on the surface that matches with parameters specified by mission scientist, mark them as targets and order the ChemCam to point and measure those targets.

Another tool from NASA is Pathogen, a new software prototype of an onboard planner. Pathogen will be tested in the Mars Science Laboratory (MSL) 2020 rover, this test and aims to replace the traditional tactical process, including high-level goals and mission execution without earth-in-the-loop [69].

However Pathogen and AEGIS software are tunned to work on Mars Science Laboratory rovers, that software or at least part of the concept behind can be adapted, compared and/or integrated with traditional techniques for UAVs.

UAVs Planetary Exploration scenarios are partially observable, this is because of the lack of detailed maps, the environmental conditions such as wind, temperature and also uncertainty in perception.

Techniques for planning and navigation of mobile robots in partially observable environments were introduced in 1998 [70]. Methods such as Markov Decision Processes (MDP) and Partially Observable MDP (POMDP) were proposed as suitable options to model and handle the mission planning and navigation of robots. The model of a problem such as UAV exploration requires at least the most important features and states of the environment, the UAV platform and a reward/penalty structure. The solution to an MDP or POMDP problem is an optimal policy to navigate and take decisions [71].

Both MDP alone or POMDP alone or a combination of both can be used for UAV navigation and mission planning.

MDP— Markov Decision Process (MDP) is a mathematical framework for modelling decision-making in situations where there is uncertainty in action or motion, for an agent interacting in a fully observable environment [72]. MDP is useful to get sequentially from one state to another in a non-deterministic environment, dealing with the uncertainty of actions or movements but assuming complete and perfect perceptual abilities [71]. An MDP model of a problem is composed by an initial state [S_0] (which belong to the possible states), a finite set of states [S], actions [A], rewards for every state [R(s)] and a transition function [T(S, A, S′)] representing the probability of ending in state S′, given that the agent start in stage S and takes action A. Is possible to include a discount factor to control the time-penalty of the reward from immediate to a long time reward [Γ]. The solution formula to a problem is called a policy [π] [70]. MDP tool can be used to model different environments and levels of decision making for underwater vehicles [73] or UAVs [74].

MDP can be found used in conjunction with Bayesian Networks to integrate diagnosis modules [54], as surveillance mission planning strategy for multiple UAVs [75], to support collision avoidance and moving target tracking [76], in highly automated mission management system (MMS) when mixed with hierarchical task-network (HTN) [77], powering high-level navigation planning mixed with POMDP and Deep Reinforcement Learning [78], in UAV motion planning resilient to sensor failures using Redundant Observable MDP (ROMDP) [79] and to make robust strategy planning mixed with Linear Temporal Logic Language [80].

Nonetheless, MDP relies on the assumption that the state of the UAV is completely observable, which might not be the case for Planetary Exploration Scenario [81].

POMDP— Partially Observable Markov Decision Process (POMDP), is applicable when there is uncertainty in the action as MDP but the environment is only partially observable (such as Mars environment), that means uncertainty in the perception [70]. Observations are represented as probabilistic functions. POMDP helps to maximize the total expected discounted return for an agent starting in a specific belief having a goal marked with the maximum immediate reward.

POMDP has been used in different applications including ground roots and UAVs. Ahmadi *et al* [82] present a barrier certificate for optimality safety verification for a rover on Mars. Walker *et al* [78] used POMDP in UAV navigation to avoid obstacles, mixed with MDP to include a global navigation strategy. Fernando *et al* [83] use POMDP in UAV to navigate and explore unknown GPS-Denied environments, find targets [84] and track mobile targets [85] [86].

One of the challenges of using POMDP for UAV navigation on Earth or Mars is the computation restrictions, given the challenges of solving the curse of history (grow of histories that could start from one empty history) that grows exponentially with the planning horizon, and the curse of dimensionality it implies that a problem with n physical states deal with belief-states in an (n-1) [87].

Significant research has been conducted in order to find a way to solve modelled POMDP problems [88]. There are several POMDP solvers Benchmark test cases. The most common are the Tiger problem [71], Tag Domain [89] and rock sampling [90].

The Rock Sampling benchmark could be framed as a planetary exploration environment, in which an observable rover and rocks are modelled. Only some of the rocks have scientific value, and the rover has a long-range sensor for checking if the rock is good to sample or not, is notable that the sample is costly.

The number of possible states changes with the problem size. As an example where n is the field size (n x n) and k is the number of rocks, for a rock sample problem of n=11 and k=11 there are around 250,000 states and for a problem of n=12 and k=11 there are 300,000 possible states, this requires approaches that avoid solving all the possible states at once, given the size of the problem and the computational restrictions [90].

A POMDP problem can be solved with an on-line or off-line POMDP solver. POMDP can be useful in Planetary Exploration environments however the solution needs to be computed online on the platform [90].

*Online-POMDP Solvers—*Solving a POMDP problem faster requires approximating the solution and restrict the search space. Algorithms such as SARSOP (Successive approximation of reachable space under Optimal policies) [91] use point values instead of the continuous belief space to reduce the computation load [90]. Comparisons have been made across algorithms such as Heuristic Search Value Iteration Algorithm (HSVI), Forward Search Value Iteration (FSVI), Prioritized Value Iteration (PVI), and Point-Based Value Iteration (PBVI) (all point-based) [92], modifying and combining some of them to increase parallel performance.

Klimenko *et al* [93], propose a Toolkit for Approximating and adapting POMDP solutions In Real-time (TAPIR). TAPIR aims to manage the two major issues of the online solvers prior to 2014, the requirement of an a-priori well-know and constant-during-runtime model and the availability of a user-friendly code. TAPIR uses Adaptive Belief Tree (ABT) algorithm to advert the model problem, and a well documented modular design, including interfaces for the commonly-used Robotic Operation System (ROS) [94], and the simulator V-REP [95].

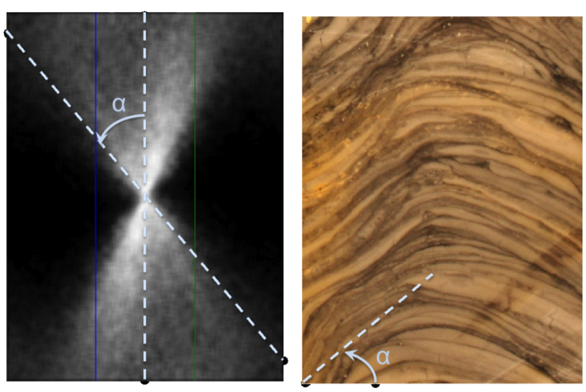
In more recent works Hoerger *et al* [96], present a new online POMDP solver, the Multi-level POMDP Planner (MLPP), this solver algorithm combines Monte-Carlo-Tree-Search with Multi-level Monte-Carlo to improve speed. The MLPP performance outperforms the current approaches such as partially observable Monte Carlo planning (POMCP), and Adaptive Belief Tree (ABT) [97].

4. BIOSIGNATURES DETECTION

Biosignatures are morphological, chemical, or isotopic traces of organisms preserved in minerals, sediments and rocks [98]. There are five potential environments on Earth and Mars for biosignatures preservation such as hydrothermal spring systems, subaqueous environments, subaerial environments, subsurface environments, and iron-rich systems. Also, six types of potential biosignatures are identified such as macro structures/textures, micro-structures/textures, minerals, chemistry and isotopes organics [99]. Figure 3 (b) shows an example of a macro structures stromatolite biosignature.

Table 4. Geological time scale with major events. Adapted from [101]

	Eonothem / Eon	Erathem / Era	System / Period	Mayor event	Age (Ga)/ Billions years Ago
	Phanero zoic	Ceno zoic	Quaternary	Diversification of life	0.00258
			Neogene		0.02303
			Paleogene		0.066
		Meso zoic	Cretaceous		0.145
			Jurassic		0.2013
			Triassic		0.2519
		Paleo zoic	Permian		0.2989
			Carboniferous		0.3589
			Devonian		0.4192
			Silurian		0.4438
			Ordovician		0.4854
			Cambrian		0.541
Precambrian	Protero zoic	Neo - Protero zoic		Plants / Small invertebrate animals	1
		Meso - Protero zoic		Multicellular life	1.6
		Paleo - Protero zoic		Atmosphere becomes oxygen-rich Eukaryotes (unicellular with nucleus and membranes)	2.5
	Archean	Neo - archean		Stromatolites / Prokaryotes (unicellular organism)	2.8
		Meso - archean			3.2
		Paleo - archean			3.6
		Eo - archean			4
	Hadeam			End of late heavy bombardment	4.6



(a) FFT (b) Original

Figure 3. FFT image (a) of Stromatolite image (b). α = 40°, steepness angles over 30° in sedimentary samples are highly related to Stromatolite [100]. ©2012 IEEE.

Biosignatures can be detected using passive (Images and spectrums) or active sensors (collecting samples). All possible autonomous techniques must be checked regularly in the early stages given the novelty of the kind of data analysed [4].

Biosignatures at micrometre scales can be detected through organic molecules identification. Standard microbiological techniques can be used, thus there are analytical techniques with relevance to robotic missions such as Raman Spectroscopy (RS), Fourier Transform InfraRed (FTIR) spectroscopy, high-resolution Laser-ablation Ionisation Mass Spectrometry (LIMS) and Elemental Analysis Isotope Ratio Mass Spectrometry (EA-IRMS). These techniques for biosignature detection are currently used or will be used in future space missions such as ExoMars [102] and Mars 2020 rover. Every single technique remain ambiguous to indicate possible biosignatures, however, mixed can unambiguously detect biosignatures [20].

The main challenge to help the direct biosignature detection is the integration of multiple coincident detection techniques with enough sensitivity, spatial and spectral resolution with an increasing spatial coverage [20], [103].

International Commission on Stratigraphy (ICS) is the largest and oldest constituent scientific body in the International Union of Geological Sciences (IUGS). Its primary objective is to precisely define global units (systems, series, and stages) [101]. The ICS has classified the geological time using 5 main groups. Those Groups from high scale to small scale are Eonothem/Eon, Erathem/Era, System/Period, Series/Epoch and Stage/Age.

The general biggest periods (Eons) are the Precambrian (composed by the Archean and Proterozoic Eons) defined as the time before 541.0 ± 1.0 Million years ago, in which most of the life was basically microscopic, and the newest namely Phanerozoic Eon which wraps 5 eras, after Precambrian to now. These groups are presented in Table 4.

The end of the Proterozoic Eon is a rich evolutionary period, triggered by changes in Earth surface such as climate, framework tectonics and biochemistry. Those changes ushered the Phanerozoic world and nourish the diversification of life[104]. The possibilities to find similar events on Mars relies on the understanding of those periods, changes, and possible life remnants on Earth [105].

A recent study carried out by Raphael Baumgartner et al [106] found a record of primordial life (organic matter) in nano-porous pyrite within stromatolites strongly sulfurized $\approx$ 3.5Ga ago in hydrothermal-sedimentary strata. These findings indicate that is possible to detect similar traces of life in the crust of Mars. Also, Remarkably similar features of hydrothermal environments on Earth was found on Mars by Spirit rover [105].

Possible implications for the preservation of organic biosignatures are related to detrital pyrite (redox-sensitive minerals preserved in sedimentary rocks that are a good Indicator of low oxygen levels prior to the rise of atmospheric oxygen in the early Paleoproterozoic (2.51.6 Ga) [107]). Also, the presence of detrital pyrite may indicate a reducing atmosphere at the time of deposition [23].

The best potential exploration targets for detecting biosignatures are wich best overlaps aspects such as Habitability, Preservation/Taphonomy, Detection and Technology available. Biosignature detection can be addressed from three main scales, the Macroscale (km), the Mesoscale (m) and the Microscale (um). The macroscale is covered by orbiters such as Mars Reconnaissance Orbiter (MRO) [43], the mesoscale and partially the microscale are achievable today using rovers and landers over the surface [108]. Future UAV mission can cover the three main scales as the technology improve.

Biosignature Detection on Mars

Detection of biosignatures on Mars is challenging. Curiosity instruments such as Mars Hand Lens Imager (MAHLI) and ChemCam Remote Micro-Imager (RMI) can take images of the interior structures and textures of centimeter-thick veins of Mars surface. These veins offer an easily accessible target and can be imaged by curiosity rover as 14 μm/pixel resolution. Veins are suitable environments for the potential preservation of microfossils within vein crystals. Also, veins can be classified and analysed using colour images based on colour, morphology and texture. Images analyses corroborated by vein chemistry are used to infer vein generation and potential formation mechanisms. Nevertheless, no clear biosignatures have been identified within vein materials on Mars [109].

Interest sites to find Possible biosignatures on Mars include Veins, organic molecules in mudstone [109].

AEGIS software on the Curiosity rover allows a more complete geological and geochemica study of the areas around the rover, autonomously collecting more data of unusual detections, suspected to be uncommon objects such as meteorites [10].

The Mars 2020 mission, for example, will use the PIXL instrument, that is X-Ray Lithochemistry sensor able to measure elementary chemistry of tiny features observed in rocks as we can see in Figure 4. In 5-10 seconds PIXL reveals major and minor elements in a sample, with 1 to 2 minutes is possible to analysed sensitive trace element, which enables the detection of potential biosignatures preservation [23].

Figure 4 shows an example of a pixel element map from a 3.45 Ga (Giga annum or billions of years) rock. These element maps reveal spatial correlations between elements, composition and textures. The elements in the sample are related to the mineralogy. Composition and texture constrain the origin and components of the rock. Elements, composition and textures on rocks can indicate geological process with implications for the preservation of organic biosignatures [23].

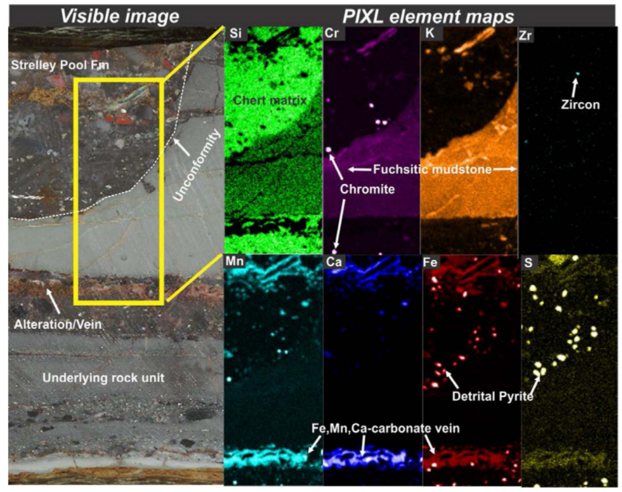


Figure 4. PIXEL element maps [23]. ©2015 IEEE.

Image Analysis

Detect biosignatures using images can be conducted using relevant features relating to pixel values (intensity and its changes), the geometry (size, orientation, shape, and smoothness of the perimeter), and position in space (derived from stereo data) [4], these features are used as well to filter, rank and prioritize the targets.

Detection of biosignatures using RGB cameras was explored by Rodney *et al* [100], (Figure 3). The use of hyperspectral images was explored by Murphy *et al*, [110]. One biosignature of high interest is the Stromatolites which are associated with the growth of microorganisms called cyanobacteria (Cyanophyta) [98].

Castano *et al* [68] indicate main step for mission planning using images processing such as acquire images, find rocks in the images, extract features from rocks, analyze and prioritize data, detect rocks that merit further investigation and plan and schedule new command sequence for the rover. Also, Thompson and Castano (Thompson and Castao 2007) compare seven classical rock detection algorithms for autonomous science.

Alexis David Pascual *et al* [111] presents a Convolutional Neural Networks (CNN) method to classify natural rocks scenes. This approach outperforms classification ability compared to methods like SVM in clean and uniform images of rocks.

Techniques like lossless compression algorithms have been proposed to differentiate sedimentary rock images with and without stromatolites based on the shape. These algorithms reduce the file size by identifying and re-coding redundant information that is related to the laminae shape of the stromatolites [112].

AEGIS contains a module called Rockster (rock segmentation through edge regrouping) that makes use of edge-detection techniques to detect closed objects contours. Rockster uses gradient-based detection (with some extra techniques) to define a first initial contour, then split it and use a gap-filling to connect fragments using the background to identify enclosed regions [113].

5. Future Work

Extract and organize a science model for detection and classification of biosignatures is an important step to feed a model for mission planning with UAV for autonomous planetary geology. Create this biosignature detection model require a geological, astrogeology, biochemistry, biology, and astrobiology expertise to define a framework to assign priorities and exploration objectives.

Databases of images from rover such as Spirit and Opportunity of Martian rocks are available [114]. In Future work, we can take these available images of Mars and apply different filters, creating synthetic pictures of possible images taken from a UAV platform on Mars. Vibration, shadows and some changes in the perspective can be analyzed and compared with real images taken from a real UAV platform.

Given the lack of images on Earth to train systems to detect biosignatures like Stromatolites, is important to conduct efforts to collect a database of biosignatures from different UAV perspectives such as heights, angles, cameras and hyperspectral data if possible, in different light conditions.

There are diverse ways to integrate and test mission planning strategies for autonomous UAV [81]. Software simulation has clear advantages like cost and time and can be conducted before the real test. Simulation environments for space exploration with biosignatures examples for UAVs are not available. A framework to simulate this environment is proposed to be developed as future work.

Suggested tools to be used in the framework include other frameworks and tools for uncluttered GPS-Denied environments [81], Gazebo [115] [116], Robotic Operating System [117] [94], V-REP [118] [95], Open Motion Planning Library [119] [120], Drona (A Framework for Safe Distributed Mobile Robotics) [121] [122] and Open Drone Map [123]. A Digital Elevation Model (DEM) of Mars can be used to simulate martian surface. Integrate biosignatures represent a major challenge. Images and scientist geological and astrobiology expertise is required to locate, tag and rank feature over the simulation environment of the framework.

Once the framework is available as a common starting point, different approaches for mission planning on autonomous UAV can be developed and tested. One suggested approach is to integrate TAPIR with Multi-level POMDP Planner (MLPP), modelling the environment and mission goals for a biosignature detection mission exploration as a POMDP problem. Other integrations such as POMDP mixed with Deep Reinforcement Learning [78] can be tested to compare performance.

In Figure 5 a proposed hardware architecture for autonomous UAV is presented, this contains the basic elements identified in the literature [53]. Also include instruments to conduct biosignature detection, such as Hi-res RGB and Hyperspectral cameras. This proposal will be integrated with off-the-shelf software for navigation in GPS-Denied environments. Off-the-shelf mission planning strategies will be tested on the proposed platforms adding planetary exploration model restrictions.

Figure 6 present the modules and the interconnection proposed to integrate de mission planning system. Mission execution is composed of different modules, a mission planning module that defines waypoints, a navigation module [83] that locates the UAV and navigates to defined waypoints, using path planners, collision avoidance and path trajectory calculator.

6. Conclusions

In this work, the autonomy, navigation and mission planning of UAVs mission for exploration of Mars and Titan were consolidated and discussed. Tools for mission planning and navigation such as MDP, POMDP and solvers were presented and reviewed. Biosignature detection and current approaches were presented. Future work and tools were also presented.

The design and validation of Drones for Space exploration rely on the results of the Mars Helicopter and DragonFly NASA flagged mission. The hardware and software design will have valuable feedback from the results of those vehicles. UAV mission planning and execution will gradually increase the complexity and science return capacity, as these platforms validate this capacity to fly on the atmospheres, and follow detailed instructions. While those validations of hardware designs and flight software take place, is advised to research into strategies to increase the science autonomy of those devices.

The rocks are the best candidate to found registers of the Mars past. The exploration of the surface and interior of Mars will help validate theories and find clues about past geology and surface characteristics.

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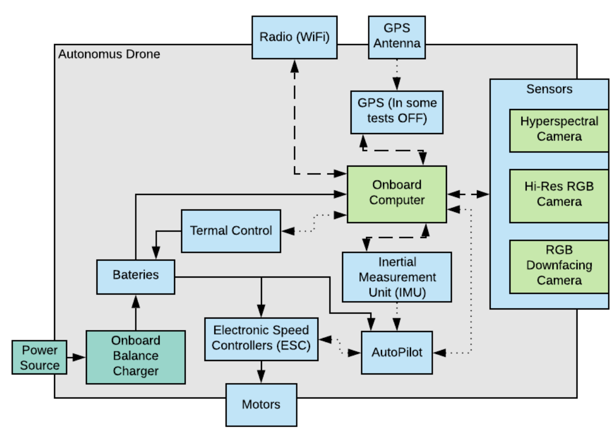

Figure 5. Hardware architecture of a proposed autonomous Drone

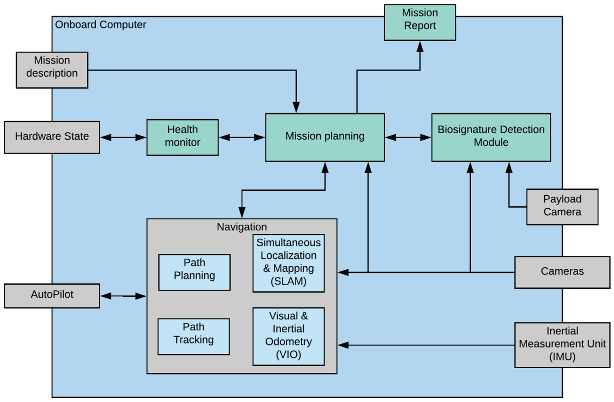

Figure 6. **Proposed software architecture**

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