*https://doi.org/10.1109/AERO47225.2020.9172467*

# A Review of Current Approaches for UAV Autonomous Mission Planning for Mars Biosignatures Detection


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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 missions 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 is still being a challenge to tame on Earth and Mars at different scales. Although new approaches to detect organic material inside stromatolites exhibit positive results for the preservation of life trails on Earth [8]. This work presents the most relevant techniques to planetary exploration.

Mars will be scrutinized further by 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 [9].

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. Furthermore, some techniques available such as MDP and POMDP are presented 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 using rovers or UAV also commonly known as drones faces several challenges that prevent real-time mission planning and execution from Earth. Round-trip communications between Earth and Mars take more than 6 minutes and for Titan almost three (3) hours [10]. Light-time latency and line-of-sight between other planets and Earth is caused by long interplanetary distances and orbital motions of the planets. The amount of data that can be collected by instruments is also increasing. 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 and cost for the mission execution [11].

Line-of-sight and data transmission-rate are problems that can be partially solved by sending more capable communication vehicles or increasing the autonomy of the system to navigate, explore and determine the best data to be sent back to Earth [11].

UAVs are and have been considered for planetary exploration due to the ability to move over the surface and through the atmosphere, which enhances the cost-effectiveness and efficiency compared to wheeled rovers or static explorers [12].

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. UAVs can also help astronauts with autonomous reconnaissance, geographical mapping, atmospheric composition and characterization, soil composition analysis, surface thermal characterization, and magnetic field measurement [4].

Several phases must be considered in the design of UAV missions for Mars and Titan, these include space transit, planet entry, deployment, and stabilization [12]. Hassanalian *et al* [4] consolidated and discussed UAV research for space exploration before 2017. Table 1 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 authors, however, concentrate on the design features and parameters selection such as weight, aerofoil rotor design, payload size and weight, variables that are carefully balanced to improve flight endurance and mission performance/capability [2].

Four main categories for UAVs, fixed-wing, rotary-wing, VTOL (Vertical Take-Off and Landing) and flapping wings have been considered for Mars [4]. These include 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 Mars Helicopter (MH) is by far, the most developed Mars UAV proposal, that fulfils the planetary exploration challenging constraints and is ready to fly. The main mission goal of the MH is to demonstrate the feasibility of using UAVs and Commercial-Off-The-Shelf electronics (COTS) for future Mars Exploration [33].

The MH mission deals with two novel concepts, a helicopter-type UAV for Mars and the use of powerful benefits, low size and reduced weight offered by COTS electronics. Components for navigation such as two Bosch SensorTec BMI160 which are Inertial Measurement Units (IMU) that measure 3-axis accelerations and 3-axis angular rates, a Garmin Lidar-Lite-V3 Laser RangeFinder (LRF) used as an altimeter, a downward-looking 640 x 480 grayscale camera (OmniVision OV7251) and a muRata SCA100T-D02 inclinometer are integrated instead of the conventional radiation-tolerant bulky, robust and expensive electronics sensors [33].

Two (2) processing units are used to face the computation requirements to fly a UAV on Mars (Figure 2), one deals with flight control and the other one with the vision-based navigation [34]. The Flight Computer (FC) consist of radiation-tolerant FPGA within a dual-core ARM Cortex-R5 microcontroller robust to radiation-induced upsets (bit flip) errors, allowing uninterrupted operation of the most critical flight control functions, such as IMU processing and down-sampling, inclinometer averaging, state propagation, fault response estimation, mode commander execution, guidance and control of the actuators [33].

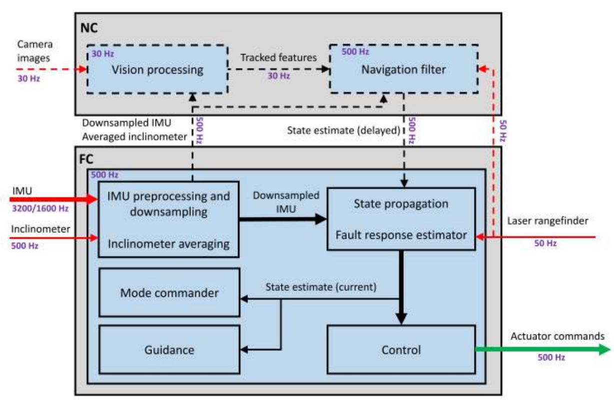



**Figure 2. Illustration of the Mars Helicopter flight control software implementation on the flight avionics, with the flow of sensor, actuator, and state estimate information. Non-realtime components are indicated with dashed lines [33].**

The Navigation Computer (NC) is based on the Qualcomm Snapdragon 801 SoC processor (2.26 GHz Quad-Core Commercial-Off-The-Shelf cell-phone processor) which ingest thirty (30) images/second from the OmniVision downward-looking camera and filtered data from navigation sensors to compute position and velocity state estimation, using the Minimal State Augmentation Algorithm for Vision-

**Table 1**. **Space Drones since 2008.**

| Name | Year | Target Body | Type 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 | Autonomous flight & Earth commanded | Vision based | - | [20] [21] |
| Mars Airplane | 2009 | Mars | Fixed-wing | - | - | - | - | - | - | - | - | [22] |
| - | 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 | - | - | - | [23] |
| MASSIVA, Halcyon, Hyperion, Y4TR | 2013 - 2016 | Mars | Fixed-wing Coaxial tilt rotor VTOL | 1000 | 60 | 25 | Explore the surface | Solar | - | - | - | [24] |
| Mars helicopter | 2014 - now | Mars | Coaxial Rotary-wing | - | 1.5 | 1.8 | Technology demonstration, scouting platform | Solar | Autonomous flight & Earth commanded | downward looking camera | Commands from Ground | [25] [26] [27] [28] |
| Prandtl-m | 2015 | Mars | Fixed-wing | 32.1 | 10 | 12.7 | - | - | - | - | - | [29] |
| 6Xsol6 | 2016 | Mars | Hexacopter Rotary-wing | - | 28 | 6.5 | Acquire data of Mars atmosphere and surface | Solar | - | Point based | Pre planned point based | [30] |
| Mars airplane | 2016 | Mars | Fixed-wing | 300 | - | 3.07 | Observe the Martian magnetic field and take close-up images | - | - | - | - | [31] |
| Marsbee | 2017 | Mars | Flapping-wing Bumblebee inspired | - | - | 2.14 x$10^{-4}$ | - | - | - | - | - | [32] |
| Dragonfly | 2016 - now | Titan | Octocopter Rotary-wing | 60 | 120 | 300 | Explore the surface and atmosphere in search of a chemistry that could foster life | Radio-active generator | - | Optical Navigation | - | [5] [6] |

- Not available or not provided

Based Navigation (MaVeN) [34].

The flagged Mars Helicopter mission aims to demonstrate a new technology capability for Mars exploration; in a risky approach but novel step towards a faster and accessible Space exploration. The Mars Helicopter could pioneer future paired mission with relevant scientific value.

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 [35]. The exploration of caves and cliffs is required to 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 [36] with significant atmosphere and water [37]. Current research aims to find remains of life on this planet, given the possibility of preservation of ancient life [38]. Mars is a cold planet, with a wide range of places in which possible ancient life may have left biosignatures. The problem of finding biosignatures is challenging for landers or rovers who cover small areas moving slowly over the rugged surface.

A Martian day named SOL is slightly longer (about 39 minutes and 35 seconds) than an Earth day [39]. Temperatures over the surface vary from lows as -140 °C during winters and up to 20 °C in summer. Surface atmospheric pressure varies between 0.4 and 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. Table 2 presents some details on the atmosphere on Earth at an altitude of 30Km which is similar to the Martian atmosphere [4].

**Table 2. Comparison of Earth and Mars Parameters adapted from [40], [24], [41], [42], [43], [44].**

| | **Earth at Sea Level** | **Earth Stratosphere ($\approx 30km$)** | **Mars** |
|---|---|---|---|
| **Gravity ($m/s^2$)** | 9.81 | 9.715 | 3.71 |
| **Atmospheric Composition** | $N_2 - 78.08\%$<br>$O_2 - 20.95\%$<br>$H_2O - 1\%$<br>Ar - 0.93%<br>$CO_2 - 0.036\%$ | $CO_2 - (ppm)$<br>$H_2 - (ppm)$<br>$O_3 - (ppm)$ | $CO_2 - 95.32\%$<br>$N_2 - 2.7\%$<br>Ar - 1.6%<br>$O_2 - 0.13\%$<br>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),<br>5-10 (fall),<br>17-30 (dust storm) |
| **Speed of Sound ($m/s$)** | 340.3 | 301.8 | 245 |
| **Dynamic Viscosity ($Ns/m^2$)** | $1.789 \times 10^{-5}$ | $1.475 \times 10^{-5}$ | $1.2235 \times 10^{-4}$ |

Orbiters such as the Mars Reconnaissance Orbiter (MRO) [45], landers as Insight [46], and rovers [47] such as Curiosity [48] have brought us information about Mars and its history. One of the remarkable findings is that Mars surface contains the chemical ingredients of life [49]. Despite the achievements and results obtained by the use of current vehicles, their limitation in resolution and the fact that they can only travel over relatively flat and smooth surfaces impulse NASA to use UAVs to explore Mars faster and deeper. In the Mars 2020 Mission, the Mars Helicopter [27] could be the first UAV heavier than air (not a balloon) used in another planet's atmosphere.

*Communication challenges—* Communication with the orbiters, rovers and landers on Mars is possible through the use of the Deep Space Network (DSN) [50]. The DSN is composed by a network of big antennas (spaced approximately 120°) over the world; one in Goldstone near California in the USA, one 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) [51].

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 [52]. The communication conditions limit the amount of data that can be sent or received from the vehicle Curiosity rover. This problem will increase with the number of active missions which make use of those communication channels; the new Mars 2020 rover, for example, has 23 cameras, nine (9) for engineering, seven (7) for science, and seven (7) for landing. With the new missions a large amount of data will be generated and must be scheduled to be sent back to Earth [53].

## 3. UAV Autonomous Mission Planning

UAV mission planning involves multiple activities including initialization of state estimator, take-off, navigation, data collection, checking the battery voltage and motor nominal performance during the flight and landing [54]. When using a charging ground station, the UAV is required to return to the vicinity of the station before landing, this maneuver includes finding the landing site using vision. After landing, the battery charging and data download process begins [55]. A health monitoring observer device is also suggested to monitor all critical components [56].

*UAV Autonomy*

Autonomy is associated with a system that uses its capacities to manage its interactions with the environment, entirely self-regulating and self-governing, taking actions that best benefits their 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 [57].

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. However, the autonomous system requires to have continuous monitoring of its resources, tasks priorities and mission risks [58].

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, it is essential to have fully autonomous hardware, which 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 [55].

Several approaches have been proposed for measuring the autonomy of a UAV system [57]. These include the draper three-dimensional Intelligence space [59], the Autonomous Control Level Chart (ACL) [58] with 9 levels from 0 (radio-controlled UAV) to 9 (fully autonomous system), the Sheridan scale for autonomy [60] and the Veres scale [61].

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 locates its position, generates its trajectories, and only requires prior knowledge about the environment, candidate goals and hazards to execute the mission [57].

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. Furthermore, science autonomy executes the planned mission using a fully autonomous hardware system, 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 [11].

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 [57].**

| 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 | Sensor for mission (Camera) |
| | Target finding | Sensors for target finding |
| | Simultaneous Localization And Mapping (SLAM) | Enhance Perception (Camera/Lidar) |
| **2) Semi-autonomous** | Collision avoidance | Perception capability |
| | Path following | Odometry |
| | Path planning | Onboard computer |
| | Autonomous departure/return | AutoPilot |
| **1) Human-operated** | Flight controller | Radio control<br>Flight capability |
| | Motor velocity control | Structure |

An autonomous UAV system can and has been achieved 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) [55].

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 [55] or having a power source onboard such as solar panels attached to the UAV [27].

There are different options for UAV autonomous charging including wireless charging [63], contact-based charging pads [27], battery swap systems [64], solar panels [26] 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 [55]. The Radioisotope Thermoelectric Generator (RTG) is only suitable for big UAVs, given the mass of the RTG, this kind of heavy UAVs can only flight efficiently in dense atmospheres and low gravity bodies such as Titan. The use of solar panels inside the UAV requires to determine a place, size of panel and mechanism to avoid the obstruction of the airflow generated by the propellers. However, onboard solar panels and RTGs free the UAV of having to land at a specific site, making possible to cover wide areas. Solar panels and RTGs can be used as a power source in ground charging stations.

There is no GPS on Mars and therefore, alternative options such as vision-based navigation and landing using a downward-facing monocular camera and distance sensors are needed. Landing has been well studied using AprilTag visual fiducial markers [65] as a lightweight and power-efficient solution, however, there are other 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 [55].

*UAV Navigation*

Navigation is the process in which a path is defined and followed controlling the movement of a vehicle between two positions [66]. 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 [67].

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 [67]. Other tools such as semi-direct visual odometry (SVO) must be used to navigate and estimate motion from a downfacing monocular camera [68].

Autonomous navigation in environments with obstacles requires a collision-avoidance strategy, some approaches are artificial potential field, vector fields histograms, dynamic window approach, velocity obstacles, path deformation, fuzzy logic and bio-inspired approaches [67].

Several methods for UAV navigation has been tested and validated on Earth, nevertheless the Mars Helicopter uses a limited vision-based navigation algorithm named Minimal State Augmentation Algorithm for Vision-Based Navigation (MaVeN) [34]. MaVeN is effectively a Visual Odometry Algorithm (VOA) based on monocular cameras.

MaVeN works detecting the relative motion of the vehicle from one down looking image to the next one, over relatively flat surfaces (10% of the flight height). However, This algorithm can not determine an absolute position or orientation accumulating a significant drift with time. That drift is acceptable for the 90 seconds flights and can be reset by an operator on Earth matching the last image after landing with a known terrain data [34].

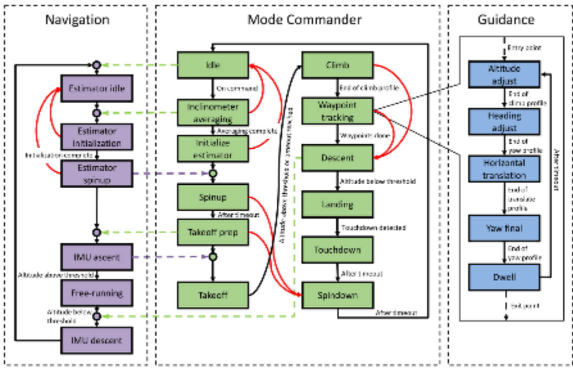



**Figure 3**. **State Machines and Mode Commander in the Navigation and Guidance subsystems of the Mars Helicopter. The dashed arrows indicate dependance of certain state to be reached in the other subsystem. The red arrows indicate fault triggered transitions [33].**

The Mars helicopter contains three main subsystems implemented as finite state machines, for navigation, guidance and mode commanding as illustrated in Figure 3. The mode commander defines the current operation state mode of the flight control system, following commands from the ground (commands sent from Earth through the Mars 2020 rover), navigation subsystem focus on the estimation of states and measurements of sensors, and the guidance subsystem allows the waypoint tracking, adjusting the position and heading of the helicopter [28].

*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 4). 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 [11], 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 4**. **The Curiosity rover mission operation process adapted from [4] and [11].**

Software tools have been proposed to make use of this dead time [1]. A tool from NASA called Autonomous Exploration for Gathering Increased Science (AEGIS) was developed as part of a larger autonomous science framework called OASIS (Onboard Autonomous Science Investigation System) [69]. 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 [57]. AEGIS looks into the images for features on the surface that match with parameters specified by mission scientist, marks them as targets and commands 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 aims to substitute the traditional tactical process, including high-level goals and mission execution without earth-in-the-loop [70].

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

One important aspect for UAVs planetary exploration is that the environment is partially observable, this is due to the lack of detailed maps, the environmental conditions such as wind, temperature and also uncertainty in perception and localization of the UAV or the target itself.

Techniques for planning and navigation of mobile robots in partially observable environments were introduced in 1998 [71]. 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. Both MDP alone or POMDP alone or a combination of both can be used for UAV navigation and mission planning [72].

*Markov Decision Process (MDP)*—MDP is a mathematical framework for modelling sequential decision-making problems in situations where there is uncertainty in action or motion, for an agent interacting in a fully observable environment [73]. 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 [72]. An MDP model of a problem is composed by an initial state (($S_0$) (which belongs to the set of 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.

It is possible to include a discount factor to control the time-penalty of the reward from immediate to a long time reward ($\Gamma$). The solution to a problem is called a policy ($\pi$) [71]. MDP tool can be used to model different environments and levels of decision making for underwater vehicles [74] or UAVs [75].

MDP can be found used in conjunction with Bayesian Networks to integrate diagnosis modules [56], as surveillance mission planning strategy for multiple UAVs [76], to support collision avoidance and moving target tracking [77], in highly automated Mission Management System (MMS) when mixed with Hierarchical Task-Network (HTN) [78], powering high-level navigation planning mixed with POMDP and Deep Reinforcement Learning (DRL) [79], in UAV motion planning resilient to sensor failures using Redundant Observable MDP (ROMDP) [80] and to make robust strategy planning mixed with Linear Temporal Logic language (LTL) [81].

Nonetheless, MDP relies on the assumption that the state of the UAV is completely observable, which might not be the case for a planetary exploration scenario [82].

*Partially Observable Markov Decision Process (POMDP)—* POMDP is a method applicable when there is uncertainty in the action as MDP but the environment is only partially observable (such as Mars environment), and when there is uncertainty in perception [71]. Observations are represented as probabilistic functions. POMDP aims to calculate an optimal policy that minimises a total expected discounted return for an agent starting in a specific belief (state) and having marked goals to explore.

POMDP has been used in different applications including ground robots and UAVs. Ahmadi *et al* [83] present a barrier certificate for optimality safety verification for a rover on Mars. Walker *et al* [79] used POMDP in UAV navigation to avoid obstacles, mixed with MDP to include a global navigation strategy. Vanegas *et al* [84] use POMDP in UAV to navigate and explore unknown GPS-Denied environments, find targets [85] and track mobile targets [86], [87]. However none of those approaches considered a Mars environment exploration using UAVs.

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 (growth 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 a *number of physical states n* deal with *belief-states in an (n-1)* [88].

Significant research has been conducted in order to find a way to solve modelled POMDP problems [89]. There are several POMDP solvers Benchmark test cases. The most common are the Tiger Problem [72], Tag Domain [90] and Rock Sampling [91].

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 take a sample is costly.

The number of possible states changes with the problem size. As an example for a rock sample problem where n is the field size (n x n) and k is the number of rocks, for 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 [91].

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 [91].

*Online-POMDP Solvers—* Solving a POMDP problem is complex and requires restricting the search space and approximate the solution [82]. Algorithms such as SARSOP (Successive Approximation of Reachable Space under Optimal Policies) [92] use point values instead of the continuous belief space to reduce the computation load [91]. 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) [93], modifying and combining some of them to increase parallel performance.

Klimenko *et al* [94], 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 to be more user-friendly, including interfaces for the commonly-used Robotic Operation System (ROS) [95], and the simulator V-REP [96].

In more recent works Hoerger *et al* [97], 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) [98].

# 4. BIOSIGNATURES DETECTION

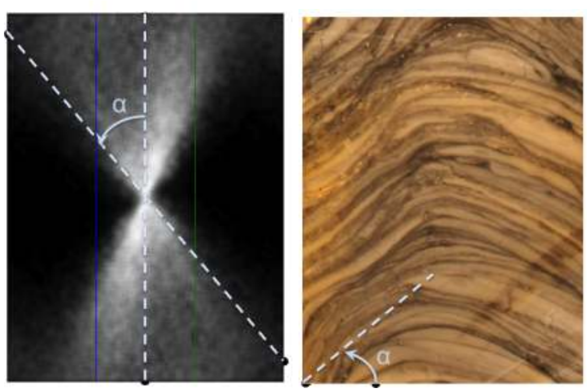
Biosignatures are morphological, chemical, or isotopic traces of organisms preserved in minerals, sediments and rocks [99]. There are five potential environments on Earth and Mars for biosignatures preservation such as hydrothermal spring systems, subaqueous environments, subaerial environments, subsurface environments, and iron-rich systems. There are five common types of potential biosignatures including macro-structures/textures, micro-structures/textures, minerals, chemistry and isotopes organics [100]. One biosignature of high interest is the stromatolites (structures/textures) which are associated with the growth of cyanobacteria (Cyanophyta) microorganisms [99]. Figure 5 (b) shows an example of a macro structures stromatolite biosignature.

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 and there are analytical techniques with relevance to robotic missions including: 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 [103] and Mars 2020 rover. Every single technique has some degree of uncertainty to indicate possible biosignatures, however, when mixed together

**Table 4. Geological time scale with major events. Adapted from [102].**

| | Eonothem / Eon | Erathem / Era | System / Period | Major event | Age (Ga)/ Billions years Ago |
|---|---|---|---|---|---|
| | Phanerozoic | Cenozoic | Quaternary | Diversification of life | 0.00258 |
| | | | Neogene | | 0.02303 |
| | | | Paleogene | | 0.066 |
| | | Mesozoic | Cretaceous | | 0.145 |
| | | | Jurassic | | 0.2013 |
| | | | Triassic | | 0.2519 |
| | | Paleozoic | Permian | | 0.2989 |
| | | | Carboniferous | | 0.3589 |
| | | | Devonian | | 0.4192 |
| | | | Silurian | | 0.4438 |
| | | | Ordovician | | 0.4854 |
| | | | Cambrian | | 0.541 |
| Precambrian | Proterozoic | Neo - Proterozoic | ... | Plants / Small invertebrate animals | 1 |
| | | Meso - Proterozoic | | Multicellular life | 1.6 |
| | | Paleo - Proterozoic | | 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 5. FFT image (a) of Stromatolite image (b). $\alpha$ = 40°, steepness angles over 30° in sedimentary samples are highly related to Stromatolite [101].**

they can unambiguously detect biosignatures [35].

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 [35], [104].

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) [102]. 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.

It is possible to understand biosignatures on Mars by looking at the main geological periods on Earth (Eons). These are a) The Precambrian (composed by the Archean and Proterozoic Eons) defined as the time before $541.0 \pm 1.0$ Million years ago. These periods are where most of the life was basically microscopic, and the newest, b) The Phanerozoic Eon which includes five (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 [105]. The possibilities to find similar events on Mars relies on the understanding of those periods, changes, and possible life remnants on Earth [106].

A recent study carried out by Raphael Baumgartner et al [8] 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 by the Spirit rover on Mars [106].

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]). The presence of detrital pyrite also may indicate a reducing atmosphere at the time of deposition [38].

The best potential exploration targets for detecting biosignatures are those which overlaps aspects more 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 ($\mu m$). The macroscale is covered by orbiters such as Mars Reconnaissance Orbiter (MRO) [45], 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*

Elements, composition and textures on rocks can indicate geological process with implications for the preservation of organic biosignatures [38]. 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 $14\mu m/pixel$ resolution. Veins are suitable environments for the potential preservation of microfossils within vein crystals. Also, veins can be classified and analysed using colour images, 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 and organic molecules in mudstone [109].

The AEGIS software on the Curiosity rover allows a better geological and geochemical study of the areas around the rover. Once the rover arrives at a new location, the AEGIS software autonomously collect data at this location, focusing on detecting uncommon objects such as meteorites, different rock composition/texture or different geological features [11].

The Mars 2020 mission, for example, will use the PIXL instrument, which is an X-Ray Lithochemistry sensor able to measure elementary chemistry of tiny features observed on rocks as shown in Figure 6. Within 5-10 seconds PIXL reveals major and minor elements in a sample, after 1 to 2 minutes, it is possible to analyse sensitive trace element, which enables the detection of potential biosignatures preservation [38].

Figure 6 shows an example of a PIXL element map from a 3.45 Ga (Giga annum or billions of years) rock on Earth. 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.

*Image Analysis*

Detection of biosignatures using images can be conducted using relevant features which relate 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 by scientists to filter, rank and prioritize targets for more detailed sampling.

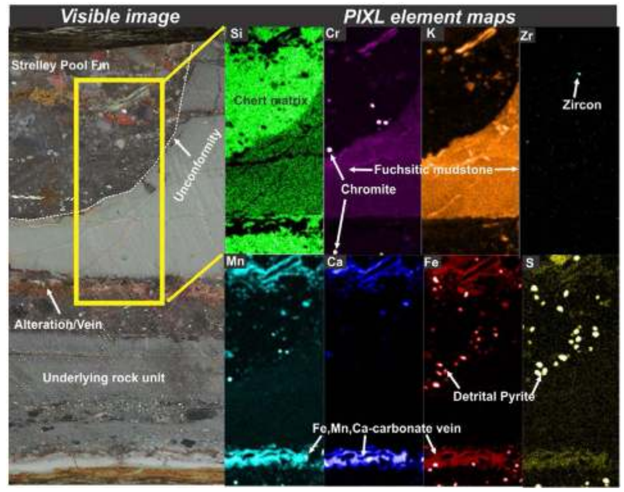



**Figure 6. PIXL element maps [38].**

Detection of biosignatures using RGB cameras was explored by Rodney *et al* [101], running an FFT analysis over the images presented in Figure 5 a looking for repetitive patrons and angles on images related to stromatolites. This work highlights the necessity of a large image dataset and more diverse set of images taken on less ideal conditions (light, angles, not clean-cut rocks).

The use of hyperspectral images was explored by Murphy *et al* [110], revealing complex patterns, and large differences between biogenic and non-biogenic samples.

Thompson and Castano [111] compare seven classical rock detection algorithms for autonomous science and present a performance analysis using images of Earth and Mars. Castano *et al* [69] indicate main step for using image processing for rover mission including image acquisition, finding rocks in the images, extraction of features from rocks, analyze and prioritize data, detection of rocks that merit further investigation and plan and schedule new command sequence for the rover cameras for further inspection.

Pascual *et al* [112] 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 [113].

Another technique currently used by AEGIS is Rockster (rock segmentation through edge regrouping). Rockster makes use of edge-detection techniques to identify 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 [114].

## 5. FUTURE WORK

Extracting and organizing 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. Several objectives need to be considered in order to create this biosignature detection model. Important topics such as geological, astrogeology, biochemistry, biology, and astrobiology expertise define a framework to assign priorities and exploration objectives.

Databases of images from rovers such as Spirit and Opportunity of Martian rocks are available [115]. In future works, we can take these available images of Mars and apply different filters in order to create synthetic 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, it is important to collect a database of biosignatures from different UAV perspectives such as heights, angles, cameras and hyperspectral data if possible, in different lighting conditions.

There are diverse ways to integrate and test mission planning strategies for autonomous UAV [82]. 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 [82], Gazebo [116], [117], Robotic Operating System [118], [95], V-REP [119], [96], Open Motion Planning Library [120], [121], Drona (A Framework for Safe Distributed Mobile Robotics) [122], [123] and Open Drone Map [124]. 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 [79] can be tested to compare performance.

In Figure 7 a proposed hardware architecture for autonomous UAV is presented, this contains the basic elements identified in the literature [55]. It also includes instruments to conduct biosignature detection, such as Hi-res RGB and Hyperspectral cameras. This proposal will be integrated with state-of-the-art software for navigation in GPS-Denied environments. State-of-the-art mission planning strategies will be tested on the proposed platforms adding planetary exploration model restrictions.

Figure 8 presents a modular system architecture proposed to integrate the mission planning system. This system architecture includes a mission planning module that defines waypoints, a navigation module [84] that locates the UAV and navigates to defined waypoints, using path planners and collision avoidance modules.

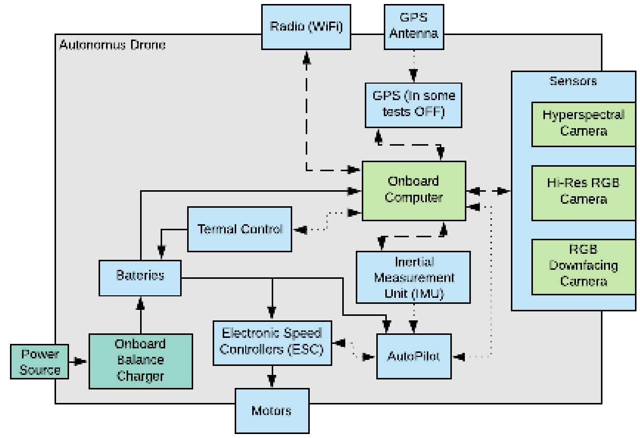



**Figure 7. Proposed hardware architecture.**

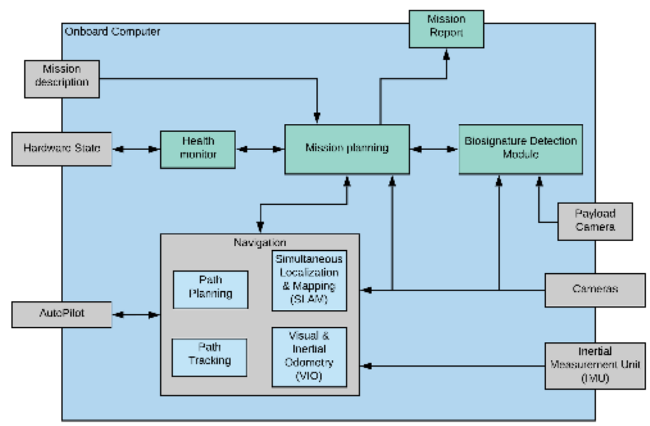



**Figure 8. Proposed software architecture.**

## 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 could benefit significantly 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 the implementation and deployment of such vehicles in real environments. UAV mission planning and execution will gradually increase the complexity of feasible missions 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, it is suggested to research into strategies to increase the science autonomy of those devices.

The use of drones to explore planetary surfaces could materialize an unreachable capacity to cover wider and complicated areas for rovers such as cliff and steep hills. This exploration approach will increase the coverage of places and rocks, raising the probabilities of detecting vestiges of the Mars past events and signs of preserved ancient life (biosignatures). The exploration of the surface and interior of Mars will help validate theories and find clues about past geology and surface characteristics.

## ACKNOWLEDGMENTS

The authors thank the Australian Research Council and Queensland University of Technology for funding this project.

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