NEXT-GENERATION ROVER GNC ARCHITECTURES

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ABSTRACT

Future Martian surface exploration missions will demand a higher scientific return compared to the current missions. Therefore future planetary rovers will require levels of autonomy that would enable them to achieve mission objectives with little intervention from ground control at very high traverse speeds. Missions that require absolute rover localisation remain a challenging problem due to the absence of helping technologies such as Global Positioning Systems (GPS) on extraterrestrial planets. The aim of this research is to propose Guidance Navigation and Control (GNC) architectures with autonomous capabilities that would potentially address the limitations in current state of the art for future Martian missions (e.g., Sample Fetch Return (SFR)). Using the current GNC architecture proposed for the ExoMars rover as a stepping stone, knowledge and understanding about the latest in navigation and mapping techniques, this paper will propose a number of GNC architectures with the potential for application to future planetary exploration missions.

Key words: Planetary rovers, GNC architectures, Rover autonomy.

1. INTRODUCTION

Future planetary exploration missions will seek to expand upon the quantity, depth and diversity of scientific return compared to current missions. Some of the potential scenarios may include sample-return missions, geographical and geological surveys of larger areas and more precise localisation of specified objects of interest. Such complex mission scenarios introduce very challenging problems, most importantly; for the rover's Guidance, Navigation and Control (GNC) system. Significantly reduced traverse times, without any compromise on localisation accuracy is a key critical requirement. This requires an increased level of autonomy compared to the current state-of-the-art in rover GNC systems, allowing planetary rovers to reach targets more quickly and more precisely, such as, the suggested 180 m/Sol traverse speed required for the Sample Fetch Return (SFR) mission [2], whilst safeguarding the safety and integrity of the rover platform.

The GNC system [10] forms a crucial part of a planetary rover, allowing it to negotiate a path through challenging unstructured extra-terrestrial terrain. The GNC architectures used in current missions constrain the traverse speed of existing rovers, especially when driving mode is required to be fully autonomous. Firstly, the autonomous driving mode in current architectures follows a Sense-Model-Plan-Act (SMPA) paradigm requiring the rover to halt periodically, substantially reducing traverse speeds (i.e. The Mars Science Laboratory (MSL) currently achieves a speed of 0.56 cm/s in autonomous SMPA-based drive mode). Secondly, the lack of logging landmark features using machine vision inevitably requires human intervention to absolutely localise the rover using orbital images [16], which given limited communication windows severely increases the time needed to accurately localise the rover. This gives rise to the third problem; it is impossible to autonomously traverse back to the lander in case of SFR missions within the required timescale. The objective of this research work is to propose GNC architectures that will address these limitations, with the potential for application to future planetary exploration missions.

In order to move beyond state-of-the-art, the proposed next generation GNC systems build upon the architecture proposed for the ExoMars rover [10], complemented with some of the latest available techniques in machine vision and terrain mapping. An example SFR mission with a traverse of 20 km over 180 sols was defined as a template in order to set the requirements specifications for the proposed systems (i.e., 180 m/Sol traverse speed, which translates to 2.27 cm/s in a 2.2 hour traverse per Sol). The major contributions of this research work involve the development of innovative GNC architectures that potentially satisfy the requirements based on theoretical underpinnings and analysis. One principal innovation for better localisation and higher navigational speed is replacement of the currently well-known method of visual odometry with a quasi-Simultaneous Localisation and Mapping technique, which has been made possible via novel visual feature detection, ground and orbital map fusion and hazard avoidance methods. It is ultimately envisaged that the proposed architectures will form the basis for the development of future rover GNC systems that will be incorporated in more complex and ambitious planetary exploration missions.

2. BACKGROUND: MER, MSL & EXOMARS GNC ARCHITECTURES

2.1. Architecture

Control architectures can be classified into three broad categories: Deliberative (Centralised) navigation, Reactive (Behaviour-based) navigation and hybrid (Deliberative - Reactive) navigation [11] and [12].

To date, most of the autonomous navigation architectures for planetary exploration rovers are based on the Sense-Model-Plan-Act (SMPA) paradigm as it is most suitable for quasi-static environments. While this deliberative approach ensures that the safety of the rover is not compromised, by rigorous assessment of the environment and planning its next course of action, the primary drawback however is that the data must pass sequentially through all stages therefore placing an unavoidable delay in the loop between sensing and action. For example the autonomous navigation software, *GESTALT*, running on several JPL rovers [4], updates a navigation map with nearby hazards from a stereo image pair, which can take up to 3 minutes for a single stereo pair to be processed [4]. To improve traversal speed, MER rovers have a reactive hazard detection algorithm that handles hazards encountered while the vehicle is moving.

The ExoMars rover will be required to cover a distance of 140 m over a 2 Sol period with full autonomy [22]. The ExoMars autonomous navigation process loop can be found in [7]. While the generated DEM within ExoMars navigation system covers a range of 4-6 m, a path that is 2 m long is planned along the least cost route [6]. On an easy terrains, it will be possible to disable the on-board production of the path (partial autonomy), in order to double the distance travelled per Sol - "fast drive" [22]. However, over a 70 m traverse the rover will end up within 7 m of a target in Martian Local Geodesic (MLG) coordinates, and with a heading within 5 degrees of the command [22]. The Data Handling System (DHS) on-board the ExoMars rover contains two independent processors: the Main-Processor and the Co-Processor [6]. While the Main-Processor runs conventional software including the mission management, communications, housekeeping, thermal management and conventional 1 Hz and 10 Hz real-time GNC software; the Co-Processor, a 96-100 Mhz LEON2 processor, is dedicated to higher intensity processes such as, navigation and Visual Odometry (VO) [6].

2.2. Mobility Design

The mobility system of the MER rover consists of six 25 cm diameter wheels with the four corner wheels having the ability to steer [16]. While the body has a 30 cm ground clearance, the baseline is around 1 m wide and 1.25 m long [4]. Speeds of 3.75 cm/s can be achieved during straight-line motion as well as a 2.1 deg/s during on-the-spot turning [4]. Although the rover is statically stable at 45 degrees, slopes greater than 30 degrees were classified as hazards [4]. Rocks with heights greater than the wheels are considered unsurmountable [4].

The ExoMars rover mobility also consists of six wheels that are 28.4 cm in diameter, each of which can be driven and steered independently [6]. The rovers footprint is 1.36 m by 1.2 m [6]. The nominal driving speed is 40 m/h (1.11 cm/s) which would satisfy the mission requirement for travelling [6].

2.3. Localisation

The MER rovers update their on-board estimate of position and attitude at a rate of 8 Hz and are based on IMU and wheel odometry data. Both blind and autonomous drive motions are typically based on simple primitive operations, e.g., straight line drives, curved arcs etc., [18]. Stereo-based Visual Odometry (VO) is used to minimise the errors in attitude and pose estimates. At least 60% of overlap between adjacent images is needed to ensure feature overlap. As such rover drive commands were limited to 75 cm in a straight line or curved arc and 18 degrees for turning on-the-spot. Due to the low processing capabilities, each step required over 2 mins of processing time therefore keeping traverses short. Slopes $>$ 10 degrees were exhibited [18]. The ExoMars rover uses a visual localisation technique from a pair of stereo cameras [22] as well. Due to the intensive processing power required, the Visual Localisation (VL) system is only capable of updating every 10 s [10]. Contrary to VO on the MER rovers, it is possible to run the VL continuously without stopping as there is enough overlap over subsequent iterations.

3. USE CASE: SFR MISSION SCENARIO

The Mars Sample Return (MSR) mission is currently being investigated for launch post 2024. Further literature on specific scientific goals and mission objectives are outlined in [1]. It is aimed at returning a number of Martian soil samples back to Earth. An integral part of the MSR programme is the *Sample Fetching Rover (SFR)* mission where the rover design needs to be significantly different from current Martian rovers due to the inherent challenging requirements demanded by the mission [2].

The SFR rover will be required to traverse much faster than previous rovers (e.g., MER and MSL) throughout its daily path with average speeds of 80 m/hr without stopping. This poses a serious challenge on the mobility and GNC designs. The proposed rover design in [2] has a few similarities with the ExoMars (e.g., 6 wheels locomotion system, similar suspension and steering setup), although with a smaller footprint. Suggested wheel dimensions and design requirements indicate that rocks greater than 15cm in height and slopes greater than 20 degrees will be unsurmountable. The computational power of the OBDH on-board the SFR rover is expected to be comparable to that of the LEON3 processor [2].

The current state-of-the-art in rover GNC systems do not have the capabilities to autonomously traverse unknown and unstructured terrains without stopping due to the heavy computational requirements. There are some speculations about offloading the computational requirements via the generation of high resolution navigation maps from orbital [2]. However, it is still unrealistic, given that the smallest rock detected with the latest orbital imagery is 0.7 m [5]. Nonetheless there is increasing confidence that this figure may be further reduced through shape from shading techniques [17, 8, 13]. As such on-board hazard perception technique within the GNC system is unavoidable.

The SFR mission was considered a good use case scenario for setting up the requirements specifications for the proposed next-generation GNC architectures.

4. PROPOSED NEXT-GENERATION GNC ARCHITECTURES

In this section, three architectures will be presented that introduce the Simultaneous Localisation And Mapping (SLAM) concept to GNC systems of planetary exploration rovers. Each SLAM based GNC architecture differs on the basis of their level of complexity, computational load and inherent risks. The ExoMars Mobility GNC architecture presented in [22] has been used as a baseline for the proposed architectures with the following important notions:

- A speed of 180 m/Sol translates to a nominal speed of 2.27 cm/s considering a 2.2 hour traverse per Sol
- An average traverse speed of 3 cm/s is assumed possible (MER was capable of achieving a speed of 3.75 cm/s)
- Generation of a disparity map from a stereo pair takes 11 s on a 100 MHz processor [10]; it is assumed that it would take 3.6 s on a 300 MHz processor

Future missions, such as the SFR will require travelling distances that are significantly greater than what is currently achievable. Most conventional GNC architectures will fail to achieve this goal as the drift in localisation grows up to a level which would compromise mission success. Applying the increased speed and distance travelled to the currently expected ExoMars localisation system performance [23], one can estimate that the maximum localisation error drift would be 3.1 m for every 180 m/Sol. As such absolute localisation will be deemed important. One potential solution is to regularly update the rover position via a satellite, which is infeasible due to operational constraints. Alternatively, the rover can map unique features within its environment locally to mitigate drifting error. This can be achieved using SLAM. However conventional SLAM algorithms are computationally intensive processes, therefore deemed unsuitable for planetary GNC systems. Fortunately, recent developments in Martian orbital imagery can generate more comprehensive maps of the terrain therefore reducing the burden on on-board computing. This knowledge of the terrain and the predicted increase in computational resources in future means that a paradigm shift towards SLAM with higher traversal speeds could be possible.

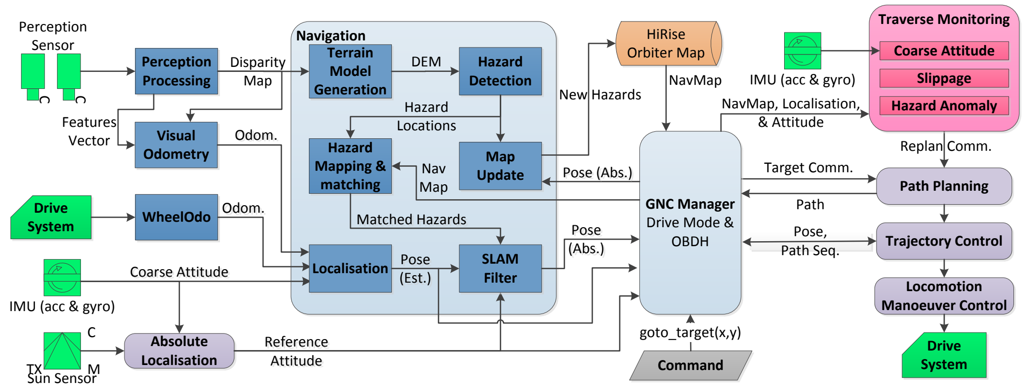
4.1. Model Based GNC Architecture with Constellation Matching SLAM

This architecture incorporates a coarse map of the terrain, as recorded from HiRise orbital imagery [9], preloaded into the system's memory (cf. Figure 1). This is a novel approach to SLAM that has only been used in landers and in terrestrial applications [15] to date.

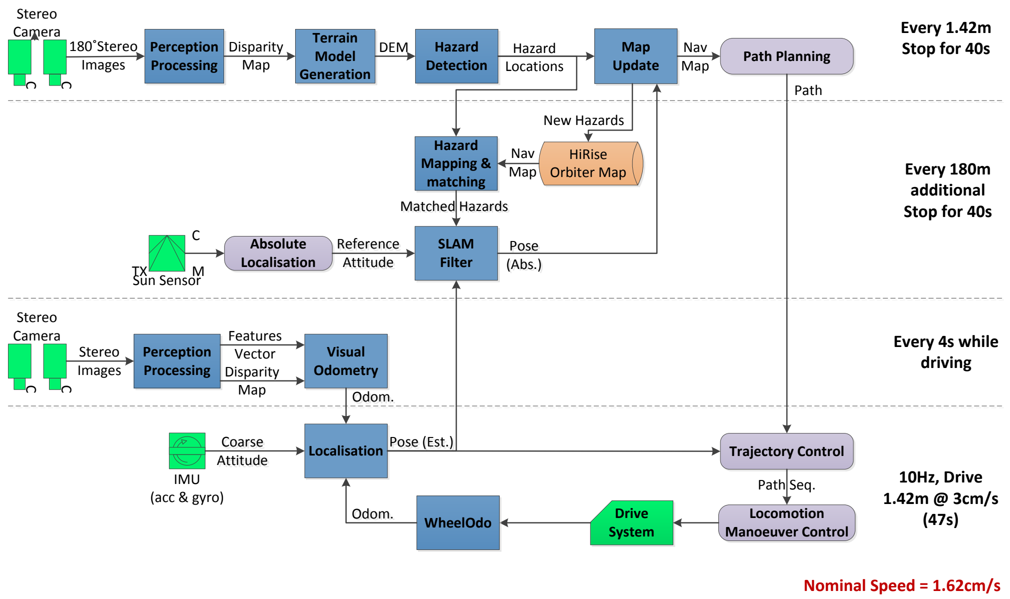
Such a map will contain locations of hazards that are 0.5 m in diameter or larger, hence the term "coarse". Average slopes of areas (approx. 1.5 m x 1.5 m) can be detected when a few grid points are used. Using a larger area yields more accurate average slope assessments. Thus it is not sufficient on its own to act as a map for navigation.

However, the map can be used for matching a pattern of hazards in a constellation with what is locally being observed from the on board sensors e.g., cameras onboard the rover (cf. Figure 2). This can be achieved by using the traditional approach of generating a DEM and assessing the hazards within the vicinity of the rover. Hazards can be filtered based on their footprint before they are matched in a constellation (such as, anything smaller than 0.5 m in diameter is removed from the matching process). Filtration ensures that the matching process doesnt attempt matching hazards that don't exist in the orbiter map. Remaining hazards within the field of view would form a pattern which serves as the search criteria for the matching process.

The area within the HiRise map at which a search for a match is performed is called the search space. The search space expands and contracts based on the current confidence of the rovers localisation. It expands when the rover moves and the localisation error drifts and contracts when a new constellation based SLAM match is found. The computation time would be dependent on the size of the search space and can be optimized. Based on an analysis of the algorithm, approximately 40 s will be required



(a)



(b)

Figure 1: Model based GNC architecture with constellation matching SLAM for exploration rovers (1a). Data pipeline and process sequence for the model based GNC architecture with constellation matching SLAM (1b).

to perform SLAM based operations for a 180 degrees H-FOV and when the error drift is estimated at 3 m (1.7% of the traverse distance between SLAM iterations).

This technique offers an approach to absolute localisation without all the complexity of conventional SLAM architectures. Consequently the observed hazards become the landmarks and the system is not burdened with keeping track of both in separate databases. This also means that the SLAM based localisation does not need to take place so frequently and triggering it a few times during a days' traverse would suffice. Although this approach provides great benefits over the traditional one, the expected gain in nominal speed is unlikely to satisfy the speed requirement for the SFR mission. Furthermore the localisation performance depends on the presence of hazards along the rover path, which cannot be guaranteed.

4.2. Reactive approach to SLAM with Constellation Matching (Type-I)

The reactive approach presented in this section (cf. Figure 3) aims at addressing further improvement in traversal speed by implementing a real-time hazard avoidance system that is based on disparity maps. Current research on such an avoidance system shows promising results [19, 20]. The objective of the obstacle avoidance process is to only alter the path sequence by veering sideways to avoid an obstacle that is on the planned path of the rover, generated once a day from the coarse navigation map (cf. Figure 4). The coarse navigation map can be loaded for a full day traverse from the HiRise map. Since this is a reactive approach, the rover will diverge from its planned path, however the trajectory controller will ensure the rover returns to its planned path. It will not be possible to run obstacle avoidance and the VO in parallel while the vehicle is moving due to computational constraints, therefore relying on wheel odometry and the

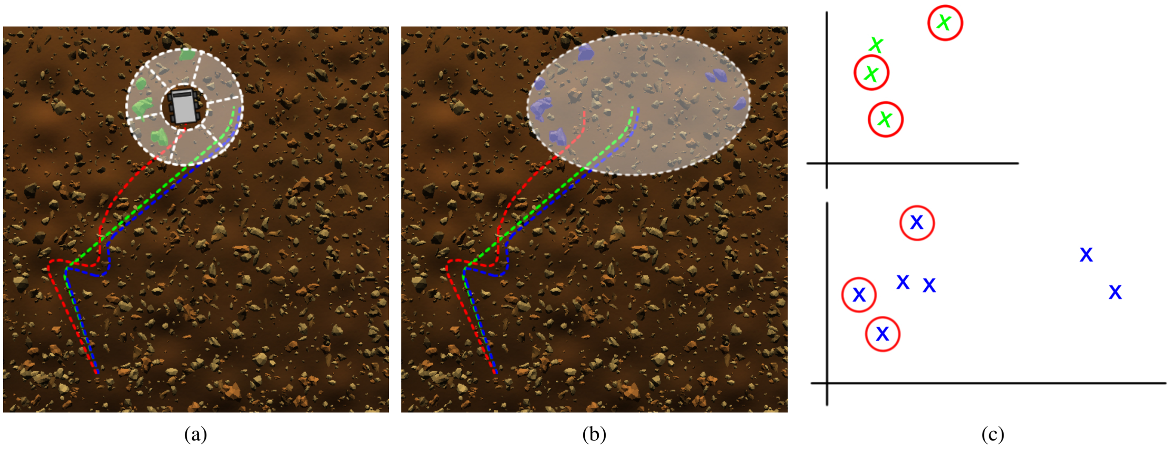


Figure 2: The green line represents the rover's planned path, the blue line represents the rover's estimated path and the red line represents the true path of the rover. In Figure 2a the rover generates local map of features greater than 0.5m. Figure 2b represents the global map using orbiter data, centred on the rover's estimated position. Figure 2c shows the matching of feature arrangements from the two maps.

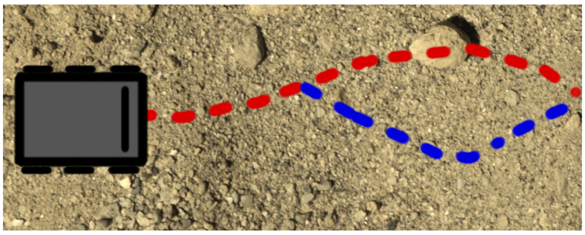


Figure 4: The rover encounters an unexpected obstacle on its planned path (red), and replans to avoid it (blue).

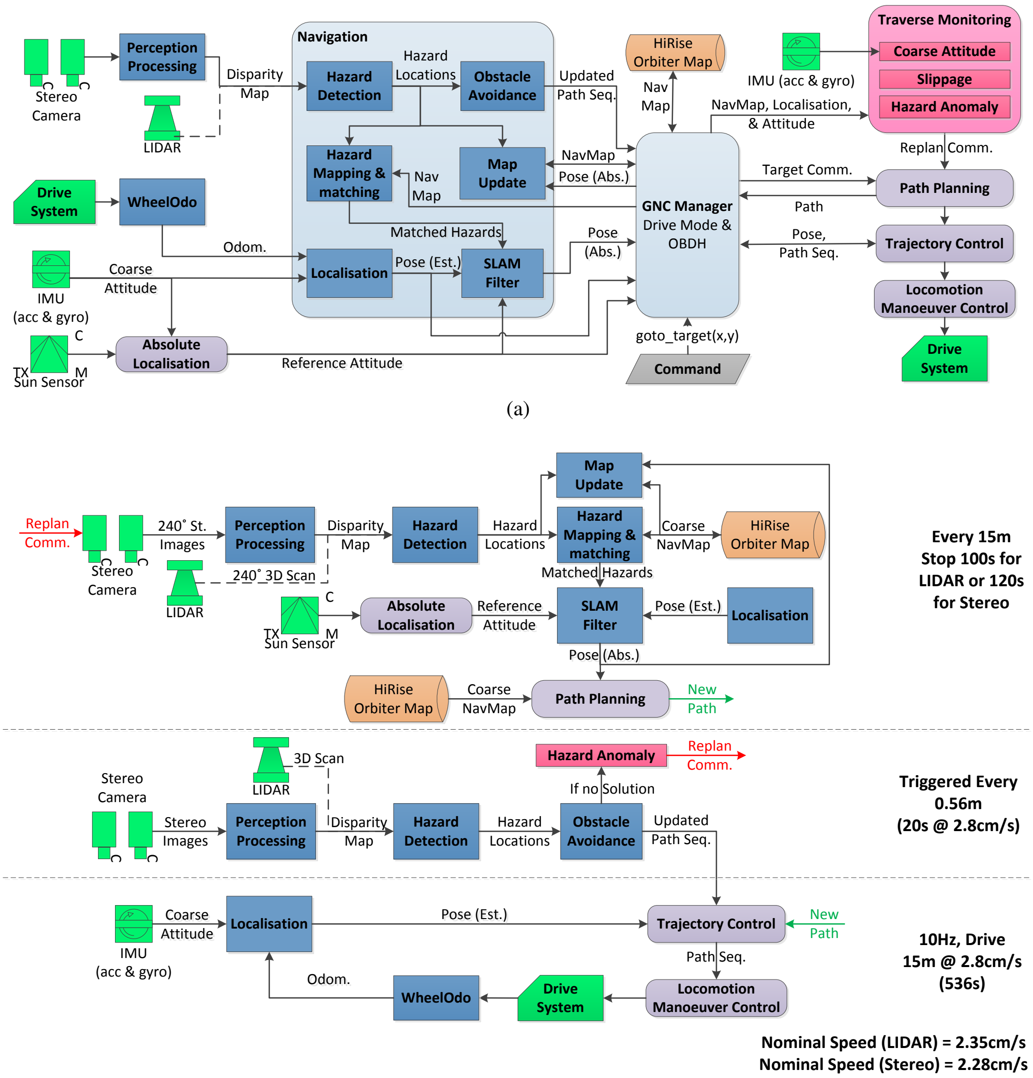
IMU only to perform relative localisation. The increase in the cumulative error due to less accurate odometry estimations will mean more frequent stops to make a SLAM based localisation. Again the range of each traverse can be optimised based on the expected level of accumulated error. Path replanning can be performed to correct for the divergence once a SLAM localisation is conducted.

This approach has its limitations: on the move environmental perception will force a narrower FOV, therefore more frequent stops would be required with an increase in obstacle density. The reactive approach would be more efficient when obstacles are sparse. The process durations are based on the assumption that most of these obstacles have very sparse distributions. It might also be possible to have the rover drive at faster speeds than the average state velocity if the control loop for the reactive hazard avoidance system is shortened, something that can be made possible by narrowing the vertical Field Of View (FOV) of the perception sensor, hence speeding up the rover velocity. On the contrary higher number of obstacles would slow down the rover to its average velocity, thus dynamically responding to terrain difficulty. Odometric estimation made via the wheel encoders and IMU in-between SLAM iterations is also a limitation. Furthermore the amount of wheel slippage cannot be detected, which may be addressed via simple optical flow operations between two consecutive depth maps. This however may not be as accurate as VL.

Although stereo cameras are good for terrain perception, the latest in 3D LiDAR systems can equally provide good terrain perception at a fraction of the processing required for stereopsis [3, 14]. The processing intervals required for each step within the proposed GNC architecture are shown in Figure 3b. These approximate measurements are based on prior knowledge of current state-of-the-art and literature. In case of stereopsis, time required to map 360 degrees view will be sufficiently high (cf. Figure 3b). For a 3D LiDAR sensor, the estimated time to sense, model, and plan will be least 20 s less than stereopsis. Knowledge of the absolute pose of the rover following SLAM procedure means locally perceived obstacles with their positions can also be added to the HiRise Orbiter Map. Note that only the obstacles the rover can detect at the time of SLAM process may be added to the HiRise Orbiter Map. Furthermore, obstacles detected while driving the 15 m between the SLAM updates will have uncertainty due to errors in localisation and might be discarded.

4.3. Reactive approach to SLAM with Constellation Matching (Type-II)

Another reactive approach with a different perception sensor setup is presented in Figure 5. This approach differs from the previous one by fusing the data between a camera and a LiDAR, further reducing computational load. The higher resolution scans are restricted to map potential rock locations within an image scene, while a coarser point-cloud is used to identify slope hazards. First a 3D LIDAR makes a synchronised scan with a rectified and calibrated image that is captured by the monocular camera. While the 3D scan is down sampled for the slope map (∼0.5 m grid spacing), the rock detection algorithm [21] segments the monocular image into rock and non-



(a)

(b)

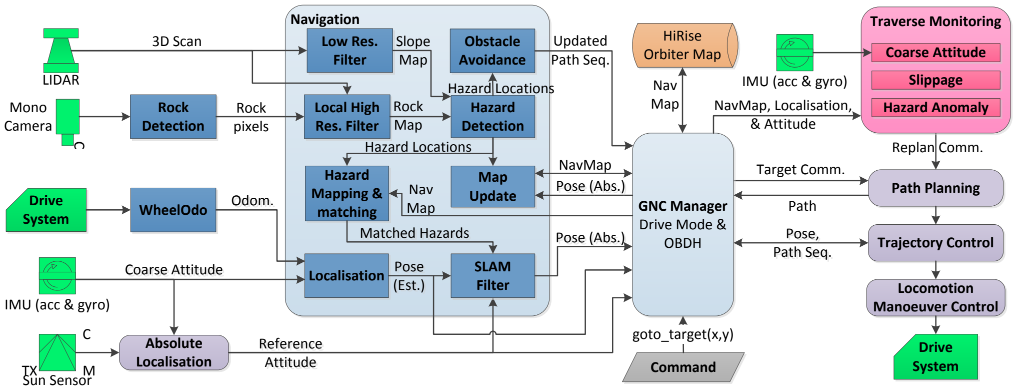
Figure 3: Reactive GNC architecture with constellation matching SLAM for exploration rovers (3a). Data pipeline and process sequence for the reactive GNC architecture with constellation matching SLAM (3b).

rock pixels which are then correlated with the 3D scan to extract their 3D shapes and locations in high resolution. The end product is a terrain model with the minimum needed resolution to safely determine hazards. The reduction in computational load means that the average speed of the rover can be reduced while still achieving the desired nominal speed and in turn reduces the burden on the mobility system.

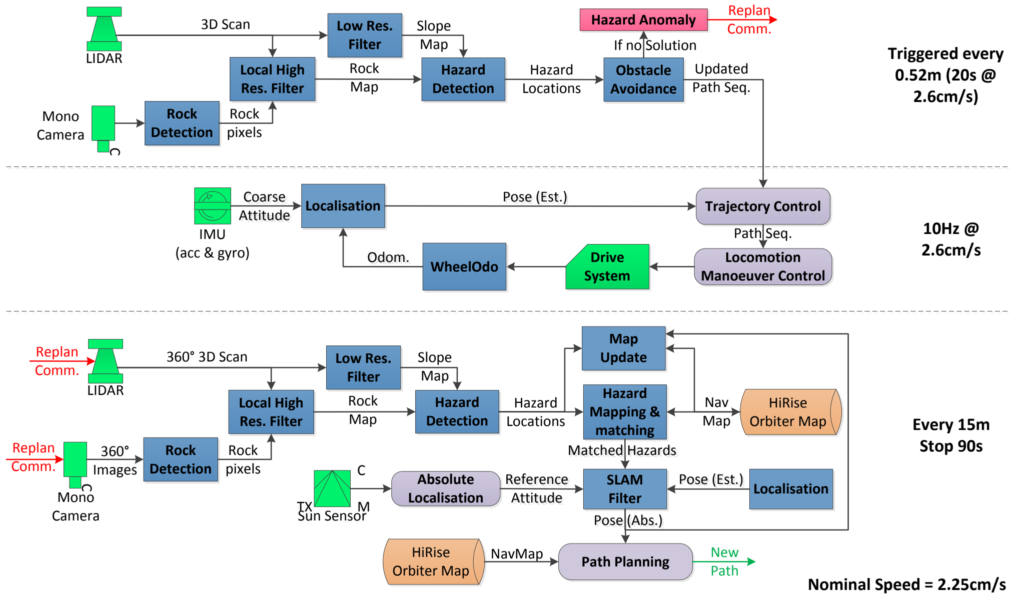
5. CONCLUSION AND FUTURE WORK

The aim of the research conducted in this project was to develop GNC architectures for the next generation of planetary rover missions. The state of the art was investigated by means of an in-depth study of past and current rover missions and the GNC architectures employed by each of them. The capabilities and limitations of these existing systems were examined, especially the traverse speeds achievable under the various conditions encountered in a planetary environment. This evaluation was used along with the baseline requirements of a prospective sample fetch return mission as a starting point for developing a set of next generation GNC. Three architectures have been developed and presented, along with top-level analysis of the benefits and shortcomings of each with respect to the mission goals.

In order to develop these architectures, potential key technologies were identified that could contribute to improving a rover's traversal speed and meeting the challenging demands of future Mars missions. Furthermore, current localisation techniques were found to be unsuitable when travelling at faster speeds and for longer distances, making the need to self-localise globally an important requirement. Five key technologies were identified as possible innovative contributions to the design and develop-



(a)



(b)

Figure 5: Second reactive GNC architecture with Camera-LIDAR fusion and constellation matching SLAM for exploration rovers (5a). Data pipeline and process sequence for the second reactive GNC architecture with Camera-LIDAR fusion and constellation matching SLAM (5b).

ment of next generation GNC:

- Orbital data
- Constellation matching SLAM
- Vision based obstacle detection techniques
- Reactive obstacle avoidance
- 3D Lidar

The three architectures presented, as well as the key technologies explored, represent a framework for developing the constituent elements of a future GNC system for planetary exploration. Using these designs as a basis, future work is planned to implement and test them. This will enable a quantitative performance estimate to be established for each individual paradigm, demonstrating the feasibility of these systems for future Martian exploration missions.

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