Wheel Slip Detection Using Auto-Correlation

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May 10, 2023

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Abstract

As the demands on exploration rovers increase, longer driving distances, higher efficiency, and increased maneuverability are needed. One aspect that will aid in these improvements is refining the speed and accuracy of detecting wheel-slip. This paper presents experimental results of statistical moments, wavelet detail coefficients, and a time-series autocorrelation analysis of signals obtained from a rover with slipping wheels. This paper considers wheel torques, forces, and motor currents. The experimental results demonstrate the signal stationarity of wheel forces and moments and thereby enables further time-domain signals analyses. After first showing that the signals are weakly stationary, the auto-correlation function was applied using a sliding window approach, creating a timeseries of coefficients. The preliminary results using autocorrelation coefficients to identify wheel slippage was not conclusive, however it demonstrates feasibility of the method. This technique does not require prior knowledge of the environment or terrain topology, which is an inherent assumption in other works.

Keywords: Slip detection, Wheeled Vehicle, Signals Analysis

1. Introduction

Martian exploration is expected to increase over the next 20-30 years [1] using a variety of robotic vehicles. Currently, the most common type of vehicle to perform surface exploration is a rover. These rovers have relatively short missions; Spirit and Opportunity had planned missions of 90 days[2], and Curiosity was expected to last 23 months[3]. These rovers performed admirably, greatly exceeding their life expectancy, and were able to last longer and drive further than initially expected. However, due to the limited range and expected lifespans of these rovers, the relatively small area they can be expected to cover limits options for exploration.

Ideally, rovers would be kept operating as long as possible to obtain more scientific information. The more types of terrain a rover can safely traverse, the more driving options a rover will have when choosing a driving path, thereby increasing the traversable ground and the amount of scientific data obtained during its mission.

By driving at slower speeds, the rover can react to a wheel beginning to slip because if a rover's wheel slips to a point where it gets stuck, the searchable area is reduced to zero. Allowing the rover more time to measure and detect a wheel's state is one factor that leads to slow driving speeds [4]. The Opportunity rover became stuck in a soft sandpit partially due to a poor ability to identify wheel slippage [5]. The cause of the rover getting stuck was not due to a mistake of the drivers, but rather the inability to adapt and identify the changing ground conditions [6]. Even though the sandpit was only a few centimeters deep and less than a meter wide, it took five Martian sols (days) to free it.

When a wheel starts to slip, the dynamics of the system change; identifying these changing dynamics make slip detection difficult. However, the specific parameters of the soil are of lesser consequence than knowing whether the vehicle is slipping or not. On the Curiosity rover, wheel current is used in part to identify wheel slippage, where if the current is high, the rover is believed to be not slipping, and when it is low, the rover is likely slipping. This type of approach suggests that there may be a signal processing method capable of identifying slippage. Autocorrelation is a tool for measuring how a signal behaves with itself and has been useful in identifying faults in hydraulic systems [7]–[10]. We believe that a similar type of signal analysis may be useful for identifying the onset of wheel slippage.

A prerequisite of time-domain signals analysis is that the signals being analyzed have at least weak stationarity[11], [12]. The work presented in this paper shows the signal stationarity analysis of forces and moments recorded from a rover test rig in a controlled setting. This paper considers the first four statistical moments and the wavelet detail coefficients of recorded signals from the test rig. This paper also presents preliminary findings on using autocorrelation for slip detection.

2. Rover Design

The rover for this project was a four-wheel design and uses no suspension system; see Figure 1. The frame for the vehicle uses V-notch aluminum extrusion. Wheel and sensor mounts are 3D printed using polylactic acid plastic (PLA) with 30% infill. All mounting hardware were steel fasteners. Four 12V motors drive the rover, each with a gearing ratio of 150:1 and a stall torque of 4.8 Nm.

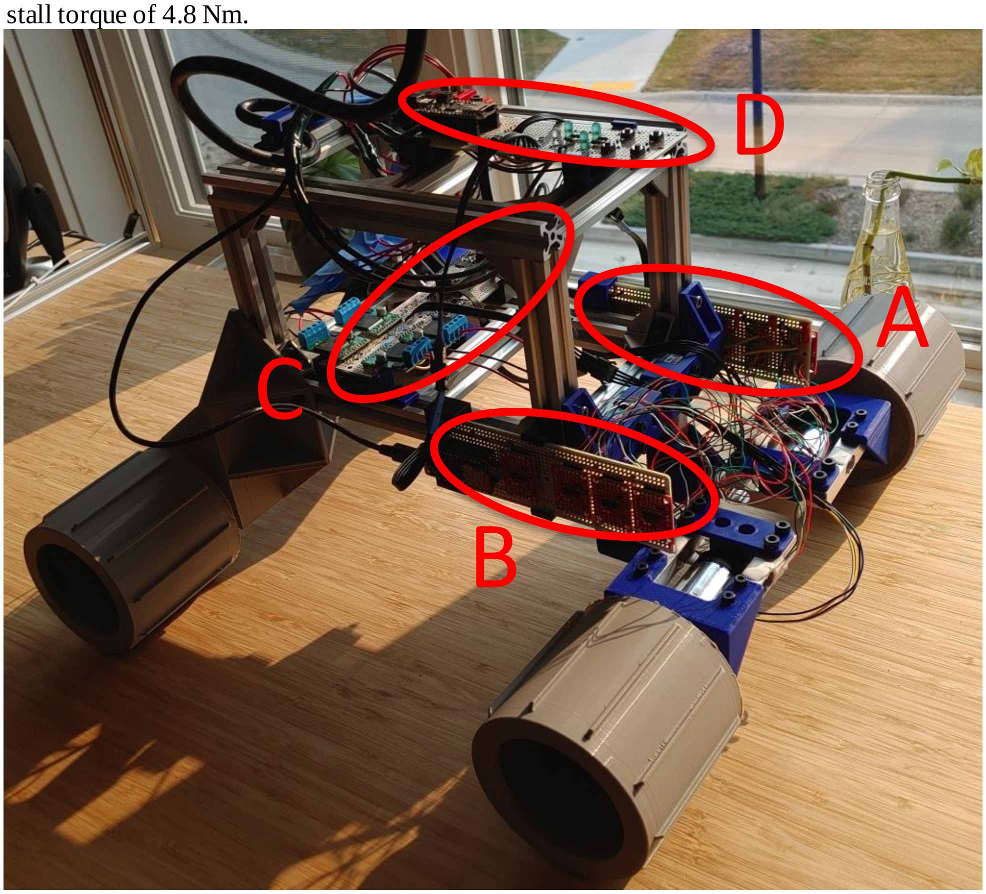

Figure 1: The rover developed for this paper, A and B are the data collection systems for the front left and right wheels, respectively. C is the data collection system for the motor currents. D is the control board for the rover.

The electronics on this rover were custom-designed for this project. The two front wheels had four load cells each. One load cell measures the forward load on the wheel while another measures the vertical loads. The remaining two load-cells mounted on either side of the wheel motors and were used to measure the torque from the motor.
These load-cells each connect to an independent 24-bit analog-to-digital converter (four per wheel). The four measurements record at 40 samples second. An independent M0 Cortex microcontroller (Adafruit "Adalogger") logged the data for each wheel, saving the data to a removable memory card. Separate microcontrollers for each wheel ensured that the logging speeds remain sufficiently fast; these sensors' boards are shown in Figure 1 as A and B.

This rover used only one wheel encoder to measure wheel speed, specifically the front right side wheel. For these experiments, the rover drove in a straight line and used an open-loop controller. A separate microcontroller from the force logging system, logged the wheel speed and each motor's current. Each wheel current was measured using a 16-bit analog to digital converter that logged at approximately 60 samples per wheel per second. This sensor is identified as C in Figure 1. A separate control board synchronizes each experiment's start and end times and commanded the logging systems to begin recording, logging data, and start/stop control of the motors.

External to the rover was a Vicon motion tracking system that recorded the rover's true position externally from the rover, from which the rover's true velocity was calculated. Four reflective tracking spheres were added to the rovers, from which the Vicon system used to identify and track the rover, recording rates for this system were at approximately 100 samples per second.

2.1 Sand Box

The Sand Box, shown in Figure 2 was a box that was 4.8 m long, 0.9 m wide, and filled with approximately 0.25 m of sand. The sand used for this project was construction-grade sand that had been filtered through a mesh, ensuring no particles were larger than 1/8 of an inch. The depth of the sand was chosen to reduce the impact of any type of boundary effects the box may have had on the behavior of the sand.

Figure 2: Sand Box used for this paper. The ridges that are shown in this image were small approximately 10 cm mounds that were created on the sand surface to represent an uneven surface and were added to induce wheel slippage. The positions of these waves were randomized in the experiments.

3. Test Setup

The following procedure was used to gather all data for this project.

· The rover was positioned outside of the sandbox on a small entrance ramp.
· The sandbox was flattened and smoothed to re-set the SandBox testbed.
· The rover self-calibrates and tared all load cells and sensors.
· The Vicon system was turned on, and the rover object was located.
· The rover then drove off an entrance ramp, which caused the rover to drop into the SandBox; this event was later used to synchronize the data from the two systems.
· The rover then drove in a straight line for 20 seconds, equating to approximately 4 m of travelled distance depending on the wheel slippage dependent.
· At the end of the experiment, the rover logged all data to its memory cards, and the Vicon data was saved.

Afterwards, the data from the three sensor systems and the Vicon system were aggregated for further analysis. This experimental procedure was repeated 38 times to gather the data sets discussed in this paper.

4. Analysis

We performed statistical moment analysis, wavelet decomposition analysis and an autocorrelation time-series analysis for this project.

4.1 Statistical Moment Analysis

To determine stationarity, we first show that a signal's statistical moments were independent of time[11]. We windowed the signal and then determined if the signal was dependent on time. Strong stationarity requires that all statistical moments be analyzed; however, for this project, only weak stationarity was required, explicitly only the first two moments. All four statistical moments (mean, variance, skewness and kurtosis) are shown in Table 1.

Table 1. Equations used in the statistical moment analysis.

Name	Equation
Mean	$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} a_i$
Variance	$\sigma^2 = \frac{(x_i - \bar{x})^2}{n-1}$
Skewness	$W = \frac{\sum_{i=1}^{n}(x_i - \bar{x})^3}{(n-1)\sigma^3}$
Kurtosis	$K = \frac{\sum_{i=1}^{n}(x_i - \bar{x})^4}{(n-1)\sigma^4}$

For the signals gathered from the rover, wheel forces in both the vertical direction and the driving direction were analyzed along with wheel torques and motor currents. These signals recorded from the sensors were then windowed using a window size from 5 to 50 data points with time steps from 1 to 40 data points for each data set. While the individual values varied, the overall trends were consistent between all of the analyses. A typical data set result is shown in Figure 3. Results were similar for the force and moment signals

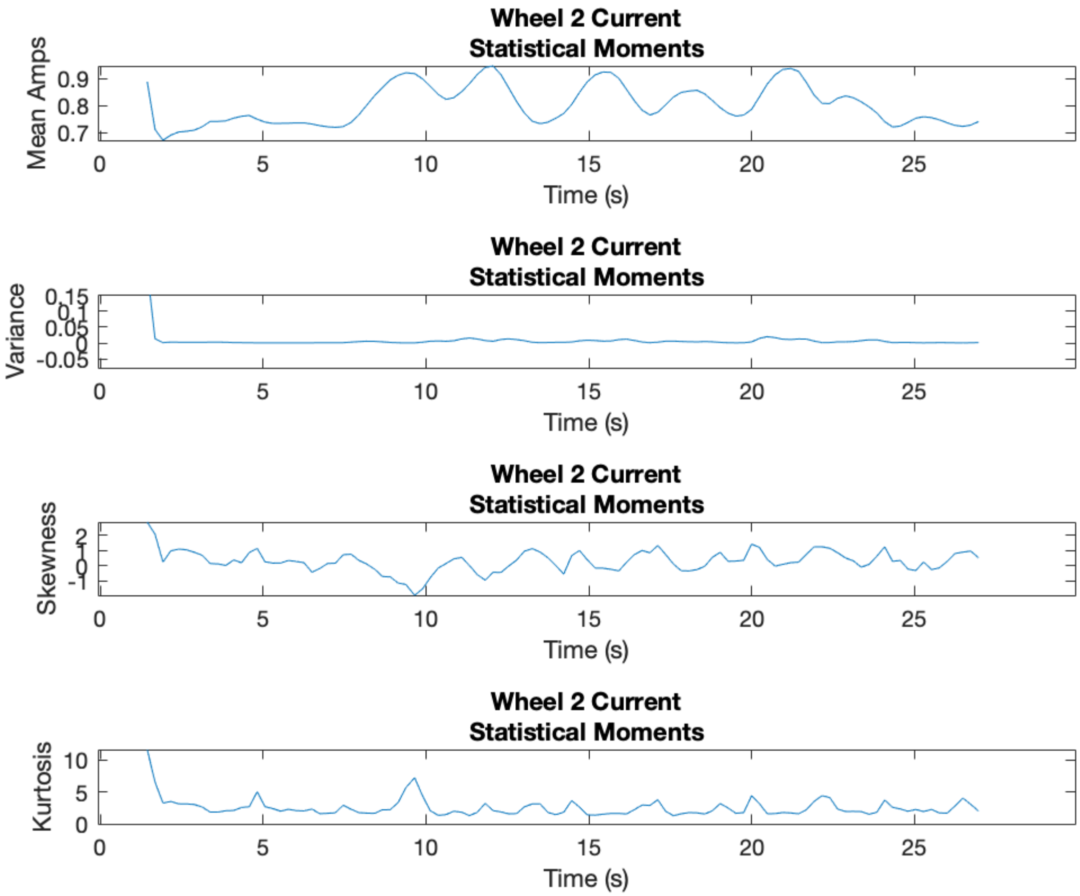

Figure 3: Statistical moments for the front right wheel of the rover using a window size of 30 data points and a step size of 5 data points.

These plots show no time dependence on the statistical moments, the values vary in time, but they do not appear to be dependent on time. This analysis suggests that the motor currents, forces, and wheel torques of the rover are not time-dependent, at least not for the duration of experiment that has been recorded

4.2 Wavelet Decomposition

The second aspect of signal stationarity is the time independence of the power spectrum. Wavelet analysis can be used as it is a time-frequency localization that is scale-independent[12]–[14]

For consistency, we used the same wheel current signal as in the statistical analysis; the detailed wavelet coefficients were calculated using the Daubechies #4 wavelet[15]. Similar analyses were performed using the wavelets from the entire Daubechies wavelet family with similar results; typical results of the wavelet detail coefficients are shown in Figure 4

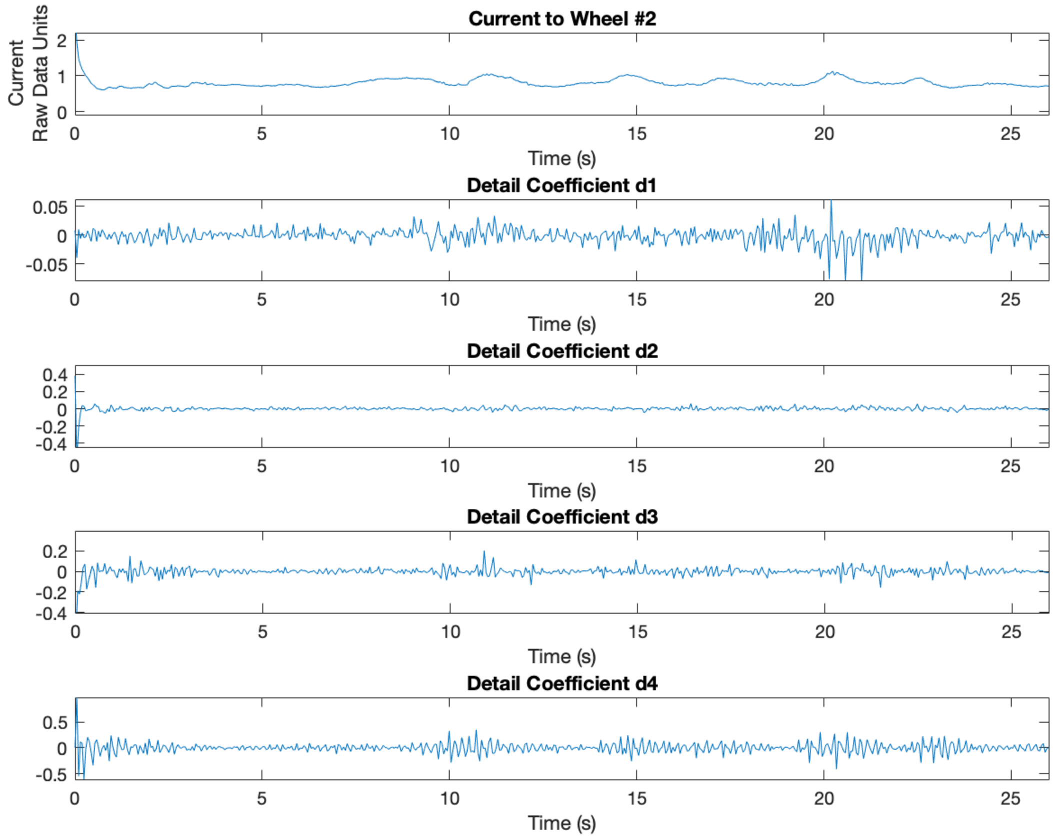

Figure 4: Wavelet detail coefficients of the number 2 rover wheel recorded currents. This analysis was performed using a window size of 30 data points and a step size of 5 data points.

As with the statistical analysis performed, no time dependence can be seen in the wavelet detail coefficients. The magnitudes and frequencies change over time but do not appear to change as a function of time. From the statistical moments and power spectrum results obtained, we can state with reasonable confidence that our rover signals are at least weakly stationary signals.

4.3 Slip Detection

The definition of wheel slippage S [16]–[18] was calculated using the angular rate of the wheel ω, the wheel's effective radius r and the true velocity of the rover V, and is shown in equation (1)

$$S = \frac{\omega r - V}{\omega r} \tag{1}$$

To calculate this value on our rover, we used the rover's position measured by the Vicon camera system. This position was then differentiated with respect to time to calculate the rover's total velocity. The wheel's angular rate was calculated from the wheel's angular position encoders and was differentiated with time. The wheel radius used in this calculation was the maximum radius of the wheel, including the tread pattern on the wheels, which was 53 mm.

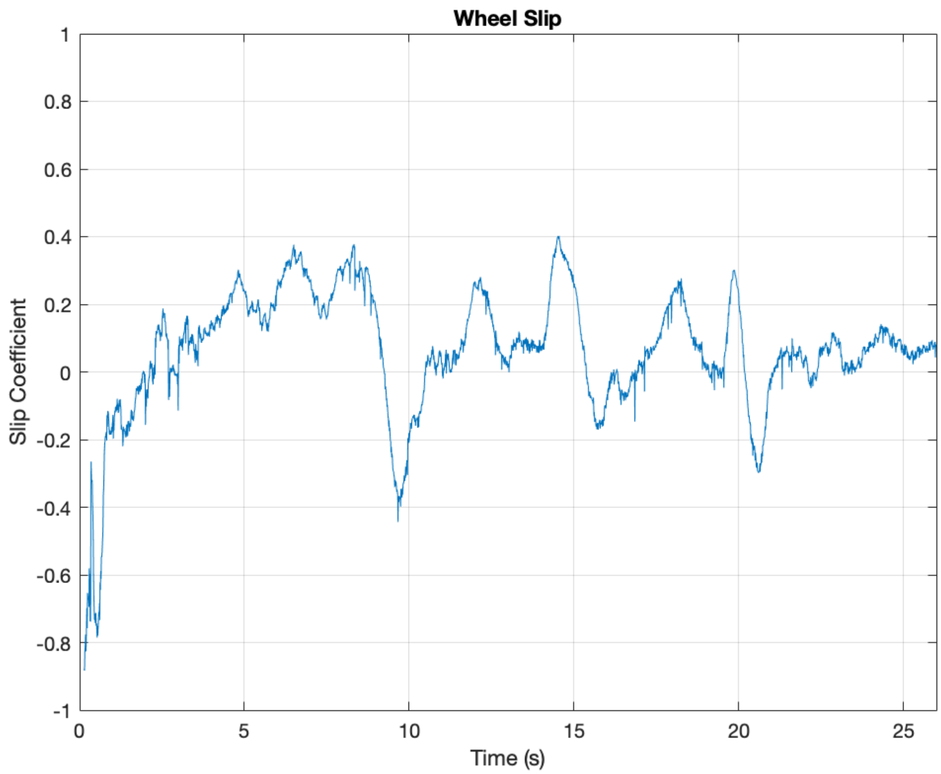

Figure 5: Wheel slippage calculated for the rover using the Vicon camera system for true rover velocity and differentiated angular position of the wheels for wheel's angular rate

Initially, from T = 0 to T = 3 seconds in Figure 5, the rover had a negative slip coefficient. A negative slip coefficient means that the rover's velocity was greater than the angular rate of the wheels. For the experiments performed, the rover dropped down off of a small lip into the SandBox. Over this short period, the rover effectively slid down a small hill, which explains the negative slippage coefficients in this plot. Similarly, at times T=10, T=15, and T=20, negative slippage values were recorded. These other segments aligned with small hills that were added to the surface of the sand and the rover was on the down side of the hill. Positive slip coefficients that are shown in this plot indicate that the wheel was producing less forward motion than was predicted using the wheel geometry and angular wheel rates.

4.4 Autocorrelation slip detection

Autocorrelation is a statistical function that compares a signal's current state to an earlier state, shifted in time [19]. Autocorrelation has been used for the identification of internal faults in hydraulic systems [8] without needing to first model the dynamics of the fault. The autocorrelation coefficients changed when a fault was introduced into the system and clearly identified that a fault had occurred. Autocorrelation may be similarly used to identify wheel slip by comparing the rotational rate of the wheel with a previous wheel rate measurement; through a change in the autocorrelation coefficients, which may indicate wheel slippage.

The autocorrelation function, shown in equation (2), takes a window of N measurements of measured signals x_i with the mean of the window $\bar{x}$. The second window of measurement is time-shifted by a non-zero integer number of measurements of τ, which is called the lag. This function produces a single coefficient, which is bounded on the interval [-1 1]. A correlation coefficient of zero indicates that the signal is completely random. A signal with a coefficient close to 1 indicates some degree of order to the signal. The equation for autocorrelation is shown in Equation (2)

$$a_{cc} = \sum_{i=1}^{N-\tau} \frac{(X_i - \bar{X})(X_{i+\tau} - \bar{X})}{\sum_{i=1}^{N} (X_i - \bar{X})^2} \tag{2}$$

For this equation to generate a time-series function, a windowing operation was needed. We used the same approach here as that used for the statistical moments. A series of overlapping windows applied to the signal generated a single coefficient for each window, thereby creating a time series of autocorrelation coefficients. The autocorrelation required a lag value and we used a series of lag values spanning from 1 through 8; typical results are shown in Figure 6.

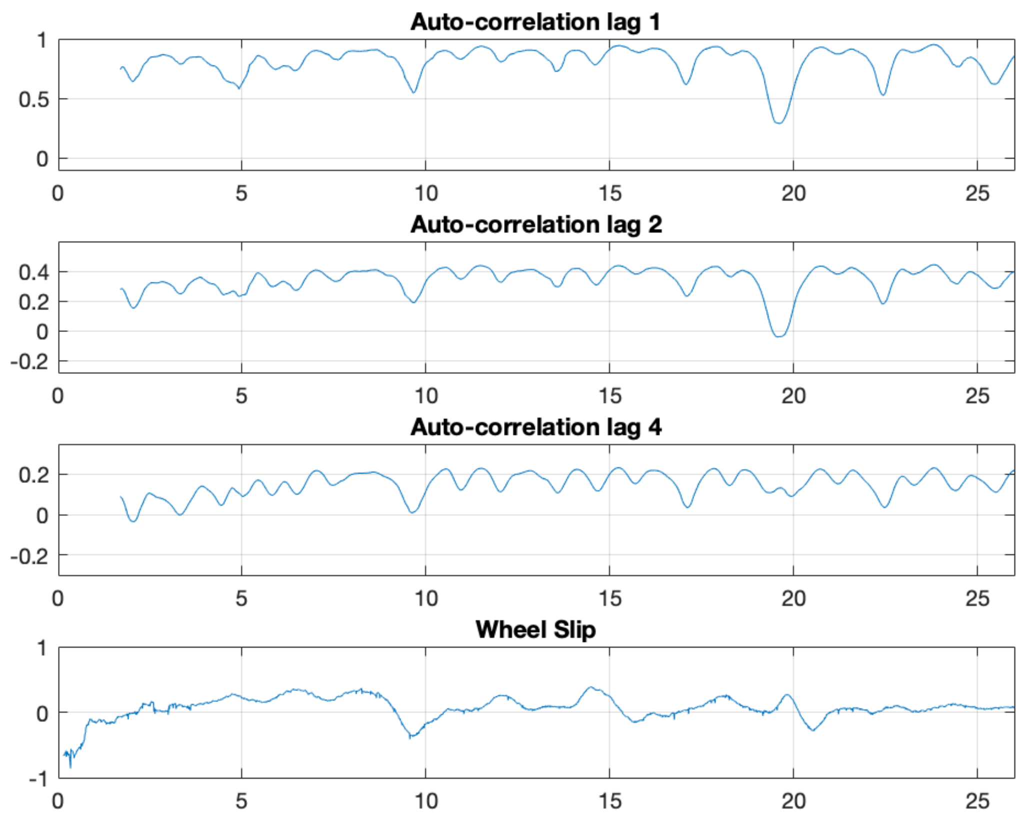

Figure 6: Wheel 2 autocorrelation coefficients at lags: 1,2, and 4, with the true wheel slippage values plotted for comparison.

This work is still in the preliminary stages; however, there appears to be a subtle connection between wheel slippage and the autocorrelation coefficients, though this is still preliminary and not conclusive. Similar plots were generated for all signals gathered from the rover. However, the strongest connection between autocorrelation and wheel slippage was found on wheel 2 of the rover.

5. Results and Discussion

This project showed that rover signals appear to be weakly stationary, as shown by the statistical moments and wavelet detail coefficients in Figure 3 and Figure 4. These findings, though not surprising, give the confidence for further analyses on these types of signals. No research could be found that had cited such findings, and this should open the door for further study into wheel slippage identification.

The autocorrelation results obtained from this project are not significant enough to state that they can be used for slip detection. However, we feel as though further investigation and refinement of the approach could still be useful. The relatively slow sampling rates of the onboard sensor systems will be improved in future work, which may help with this analysis.

6. Future Work

The work presented in this paper represents preliminary findings, and further development of both the test rig and analysis are planned. One aspect we have identified as problematic is using a single wheel encoder for vehicle speed. A single wheel speed measurement forces the assumption that all wheels have the same slippage as each other, which is known to be false under certain circumstances. Future rover developments will include all four-wheel encoders and an onboard accelerometer to allow for onboard calculation of the vehicle's velocity.
Another aspect that was not looked into in this project was the use of cross-correlation for identification. Cross-correlation is the 2D equivalent of autocorrelation, taking two signals as inputs instead of one. We think that cross-correlation may yield some indication of wheel slippage through an analysis of wheel forces in both the direction of motion and the vertical direction when compared with either the wheel torques or the angular rates.

7. Acknowledgements

This work is partially funded by an NSERC Discovery Grant (RGPIN-05363-2019), and by the CSA (18UNIRCMAN).

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