Designing a Guidance, Navigation, and Control System for the Romi Robot Kit

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***Abstract*—Our goal is to design a GNC control system for a robot to perform well in a drag race. This means the robot must maximise acceleration under wheel slip, maintain a straight line trajectory, and keep track of its distance travelled to accurately estimate the finish line. The robot we will use is an Arduino Romi by Pololu. The proposed PID heading controller shows a 41 mm deviation over a 10 meter long straight line trajectory, exhibiting a 95% improvement over a Romi without this guidance control. Furthermore, the slip traction control system completed the 10 meter race in 16.55 seconds, while Romi without any slip traction control finished in 17.52, showing a 6% slower time. Finally, the navigation tracking method proposed had an 18% improved accuracy.**

I. Introduction

Designing accurate and reliable guidance, navigation, and control (GNC) systems for vehicles is essential for ensuring that complex driving parameters are managed precisely [1]. GNC systems provide control over the movement of systems such as automobiles, ships, aircraft, and spacecraft. Each component of a GNC system is defined:

- Guidance: How the vehicle can identify the desired trajectory and adjust parameters such as rotation and velocity so that it is able to join the desired trajectory.
- Navigation: How the vehicle can accurately determine its current position and velocity.
- Control: How the vehicle can precisely perform guidance commands.

GNC systems must be robust in the environment that they are being used in. An airplane must stay straight under turbulent air, a spacecraft cannot rely on GPS if it is in space, and a ship must account for swaying and bobbing of the ocean when reading orientation [2]. We must design our systems uniquely for the tasks that will be challenging them.

A. Hardware

Our hardware is based around an Arduino Leonardo microcontroller, specifically, Romi by Pololu. We have two motors with wheels attached, making use of encoders for feedback, an Inertial Measurement Unit (IMU) chip built directly into the system, and a magnetometer sensor mounted on Romi's chassis.

B. Motivation

The aim of this project is to improve the performance of Romi in a drag race by designing and implementing an appropriate GNC system. The rules of a drag race are that two or more vehicles drive as fast as possible in a straight line over some distance, the first across the line wins. The problem occurs when we put more rotational force through the wheel than the floor's coefficient of friction can handle, causing the wheel to slip. This will not only cause unstable rotation of the vehicle, compromising straight-line trajectory, but will limit power transfer to the floor, hindering acceleration. A widely used method of tracking position uses encoders to measure the distance travelled based on the rotation of wheels, however this will become unreliable under slip. This means that Romi will not know its precise position with respect to the start line, and will likely undershoot the finish line.

C. Solution

We will implement a solution to this challenge by using hardware sensors, and PID control loops [3]. The design of Romi's GNC system will be split into three sub tasks, one for each GNC component; the guidance experiment, Section (III.A), to assess straight line trajectory, the navigation experiment, Section (III.C), to assess account of distance travelled, and the control experiment, Section (III.B), to assess maximum acceleration of Romi. Each experiment will address individual hypotheses explored for each to ensure the desired properties are upheld when under slip.

II. Technical Background

This section will present the hardware and techniques utilised in this paper. Shown in Figure 1 is a simplified diagram of Romi, along with its attached hardware.

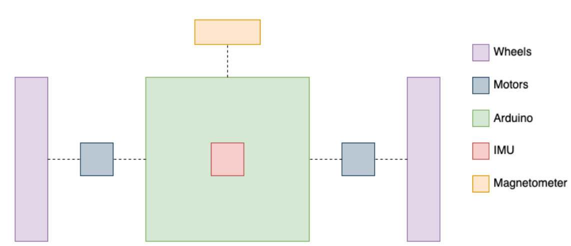

Fig. 1. Diagram of Romi.

The encoders are integrated within the motors, and the magnetometer is mounted at the head of Romi.

A. Encoders

Romi comes integrated with encoders in the motors. These sensors are able to precisely measure rotation by making use of quadrature encoding. The motor is geared to a magnet such that when the wheel spins, the magnet spins. Rotation is measured by keeping track of two bits, corresponding to two sensors that each indicate their relevant position to the magnet. These sensors are aligned such that as the wheel turns, we will have some phase shift between the two sensors. As one bit transitions, the next bit will not transition at the same moment. By evaluating which bit transitions, what transition was made, and the value of the other bit, we can find which way the wheel was turning. And by using the gear ratio between the magnet and the wheel, we can find the exact rotation that occurs with each encoder transition. Using the time taken between two consecutive encoder counts, the rotational velocity of the wheels can be calculated.

B. IMUs

The on-board inertial measurement unit (IMU) utilised for this implementation is the LSM6DS33, which features a digital accelerometer, alongside a digital gyroscope. The accelerometer measures acceleration in 3 axes and the gyroscope measures rotational velocity in 3 axes. IMUs give readings based on its relative motion rather than based on some true value anchoring. This means they can be relied on for measuring movement that is resultant of very complex systems such as wind, turbulence, and jet propulsion systems. Unfortunately, this same characteristic causes some well known issues with IMUs. These reading are very sensitive to change, so quite reactive, however since the IMU readings are always updating relative to themselves, small biases in the readings can accumulate over time to cause drift [4].

C. Magnetometers

A 3-axis Magnetometer, model number LIS3MDL, has been mounted at the head of Romi to measure orientation. Unlike gyroscopes, magnetometers are anchored to a fixed value. This means that over a long term, magnetometers are more reliable than gyroscopes as they do not suffer issues with drift. However, magnetometers can be less responsive in the short term due to the need to adjust the output to a new orientation when moving. They detect the magnetic field readings across three axes. The value for heading can be obtained using the two readings perpendicular to the desired axis of rotation. To find a value for the z-axis orientation, the $arctan$ of the x and y values is calculated.

D. Filters

Filters can be used to process signals to remove unwanted characteristics. For signals which carry substantial noise, filters can be implemented to attenuate the noise. Hyper-parameters are used to indicate the weight assigned to each input. An Exponential Moving Average (EMA) filter is a digital low pass-filter, whose formula is given by

$$output_t = \alpha * sensor\_reading + (1 - \alpha) * output_{t-1}$$

We will also be working with fusion filters; filters designed to consider readings from multiple sensors.

$$output = \gamma * sensor\_reading_1 + (1 - \gamma) * sensor\_reading_2$$

A cumulative moving average (CMA) filter is another example of a digital low-pass filter, which stores the previous n values of a signal and then outputs the equally-weighted average of the signal values. The formula for the CMA filter is given by

$$CMA_n = \frac{\sum_{i=1}^{n} sensor\_reading_{(t-n+i)}}{n}$$

Increasing the number of cumulative values stored in the CMA will decrease high-frequency noise in the signal, although it will also increase the response time of the sensor signal to stimuli, introducing lag.

E. PID Control Systems

Proportional, integral, and derivative (PID) control systems are a technique used for a closed-feedback control loop that utilises some error measurement. The error measurement is obtained by subtracting the measured output of the system from a reference desired output. The error measurement is then multiplied by the proportional gain. The error is then differentiated based on the previous reading, and a derivative gain is applied to the result. Then, the error signal is integrated over time, and an integral gain is applied to that. Finally, these three results are added and then output from the feedback system to be used in control. Increasing the proportional gain acts to increase a system's response time, but may also cause oscillatory behaviour if it is too high. The derivative gain can be used to dampen the response and oscillations caused by the proportional gain, while the integral value works to minimise the steady state error of a system over time. P, I and D values can be prioritised or ignored depending on the context of the problem. Tuning these values incorrectly can also push the system to become unstable.

III. Hypotheses

A. Hypothesis 1: Guidance

By monitoring the encoder sensors on both wheels of Romi, an accurate value for rotational velocity of the wheel can be found. This can generally be used in a closed feedback loop, such a PID control, to ensure equal speed at each wheel, and in turn straight line trajectory of Romi. When wheel slip occurs, there will be a mismatch between rotation of the wheel and forward motion, so one can no longer rely on encoder counts for straight line trajectory. The solution to this, is to make use of more reliable guidance tools, such as gyroscopes and magnetometers, to redistribute power across the wheels via a PID control system. Performance of this guidance system will be tested by comparing its straight line trajectory to that of the encoder PID implementation described. So we have our first hypothesis:

Wheel slip will likely cause rotation of Romi, and an encoder based control loop will fail to straighten

Romi due to slip making the encoder readings unreliable. We hypothesise that using a PID control system that takes a heading value measured by a magnetometer and gyroscope as its error, will result in a smaller deviation under wheel slip over a straight line trajectory than one which simply uses the encoder readings to measure the trajectory

B. Hypothesis 2: Control

The frictional force which opposes the movement of stationary objects is known as static friction. If that object is already moving, this frictional force is called dynamic friction. Static friction is greater than dynamic friction [5], meaning the force needed to transition from stationary is greater than the difference in force needed to make the same movement when already working against friction. Because of this, when slip occurs, acceleration will drop substantially. Romi will be accelerating at the maximum possible rate when its wheels are on the brink of slipping, but not quite. So we will try to improve our acceleration by implementing slip control using a proportional gain control system based on discrepancy in acceleration found between readings from the IMU and the encoders. Our second hypothesis, then, is:

With a sufficiently low coefficient of friction, hard acceleration of the wheels will cause slip, and in turn slow down Romi. We predict we can improve our drag racing performance by implementing slip control based on the discrepancy in acceleration between the IMU and encoder readings.

C. Hypothesis 3: Navigation

Wheel slip will hinder the relationship between rotation of the wheels and the distance travelled by Romi. We may be able to get a better measurement for distance by twice integrating the measurements given for acceleration by the IMU, as the accelerometer in the IMU should only be affected by actual movement, not by wheel activity. Finally, we have our third hypothesis:

Wheel slip will cause our Romi to undershoot its target distance as the encoder count will be an overestimation of movement. We hypothesise that we will get a better reading for distance travelled under slip by using an IMU as a measuring device.

IV. Experiment 1: Guidance

Experiment 1 is designed to test Hypothesis 1. This section first presents exploration of our hardware, then will discuss implementation details, and finally formalise the experiment methodology.

A. Hardware

The proposed PID heading control system must obtain an accurate and robust value for the heading of Romi. One of the sensors used to provide this measurement is the gyroscope featured in the IMU. The gyroscope's raw values carry significant noise [6], which can be attributed to the vibrations from the motors. This noise increases in amplitude as the motor accelerates, since more intense vibrations will propagate through to the on-board IMU.

We can apply an EMA filter to inhibit the high-frequency noise from the gyroscope readings, with an alpha value of 0.8 to give higher confidence to the most recent reading. The filtered heading is plotted in Figure 2 as Romi starts rotating and stops again. Since the filtered gyroscope readings closely

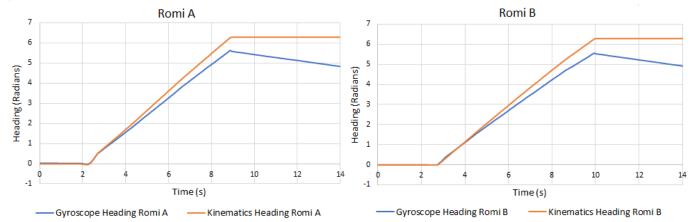

Fig. 2. Filtered Headings of Romi A and B from Gyroscope Compared to Kinematics as Romi Transitions between Stationary and Moving States.

match the kinematics readings in the short term, we conclude that the filter greatly improves the noise of our readings, and ensures that our readings are reliable in the short term. In the case of both Romis though, we start to see the detriment that drift can have to our readings as their lines start to diverge towards the end.

We next look at our magnetometer. An EMA filter with α set to 0.8 will filter noise without compromising reactivity. Plotted in Figure 3 is the heading of both Romis as obtained through the magnetometer sensors mounted on the chassis of Romi, such that we can compare the magnetometers results to that of the filtered gyroscope.

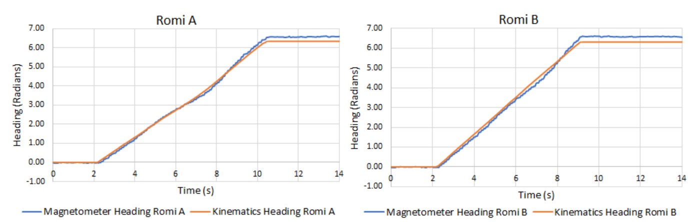

Fig. 3. Filtered Headings of Romi A and B from Magnetometer Compared to Kinematics as Romi Transitions between Stationary and Moving States.

From these figures, it can be seen that the magnetometer readings are very similar to the kinematics readings, and the accuracy of the magnetometer does not decrease over time, although it is important to note that magnetometers can be slow to react to change in orientation [7].

B. Implementation

1) Base Case: To implement our base case, we first develop a kinematics routine to measure the real time linear velocity at the edge of each wheel using the encoder counts, time elapsed, and the circumference of the wheels. Each loop of our program, our target speed of each wheel increases to achieve constant acceleration. Again, each loop, the difference between each wheel's target speed and actual speed is used as the error measurements for the two PID controllers for the left and right wheel respectively. The results from these controllers act as our power level that we should alter the motor levels by.

2) Improved Solution: We first had to decide on how to best read our value for heading. We have seen in Section (IV.A) that we can achieve reliable and stable heading results by using the magnetometer. However, magnetometers struggle with reactivity, and we know that our system must be highly reactive to correct rotation at high speeds. Thus, the readings from the filtered gyroscope and the filtered magnetometer will be incorporated will be incorporated through the use of a fusion filter. Fusing two sensor readings means that the heading values obtained are more robust to sensor glitches or issues. We are left with a heading reading that is reliable, stable, and reactive. We have our γ as 0.1 in the direction of the gyroscope so that the effects of drift are minimised, while still maintaining reactivity.

Next is to use our heading reading as input to a closed feedback loop to signal power changes to the motors. The reference signal used in the PID is zero radians, so the error signal passed to the PID controller is the value of heading as output by the fusion filter. Each loop of the program, a value of base power that is sent to each wheel is increased by 5% of the maximum power of the motor. Then, depending on the sign of the return value of the PID controller, the modulus of the return value is negated from either the left or right motor's power level to try and account for rotation measured by the heading.

The PID heading control system was tuned using trial and error methods. The proportional gain was increased until the system began to exhibit oscillatory behaviour around the zero radians point. The derivative gain was precisely tuned to dampen the oscillatory behaviour completely. The integral gain was then tuned to ensure that any steady-state error would be minimised. In the tuned PID controller, the proportional gain was 170, the integral gain was 0.1, and the derivative gain was 12000. It is important to note that the PID parameters must be re-tuned if used on different test track surface due to a change in coefficient of friction and rolling resistances.

C. Experiment Methodology

1) Overview of Method: A test track 10 meters long, in the form of a straight line of electrical tape, was set up. We sent the aforementioned base case Romi for hypothesis 1, and the improved solution down the race track, and for each repeated our experiment 10 times. Both Romis have had their tires removed to allow wheel slip to happen more easily. The criteria for success for our improved solution is the ability maintain a significantly straighter trajectory across the length of the 10m course. The results from this experiment will be averaged for each Romi.

2) Discussion of Variables:

- **Controlled Variables**: The target acceleration, the track surface and length, and the Romi used.
- **Independent Variable**: The introduction of heading control as oppose to the base case.
- **Dependent Variable(s)**: The deviation from the taped line by the end of the track, averaged across 10 runs for each case.

3) Discussion of Metric(s): We will measure the distance (in mm) between the centre of the test track and the centre of Romi at the point it crosses the finish line. A measure of heading, in radians, over time will also be plotted to ensure Romi did not deviate too far from the track throughout the run.

D. Results

The base case Romi, and the improved solution were both subject to experiment 10 times, with each of their results averaged. The average deviation from the test track after a run of 10 metres is shown below.

Exeriment 1 Results	
Romi Version	Deviation (mm)
Base Case	750
Improved Solution	41

Here we see vast improvements in the results of our improved solution compared to the base case, with a near 95% improvement rate.

When assessing our straight line performance improvement across the length of the test track, we see from Figure 4 how the improved case stabilises oscillations around zero caused by slip, while the base case's heading veers off to the side with no attempt of correction.

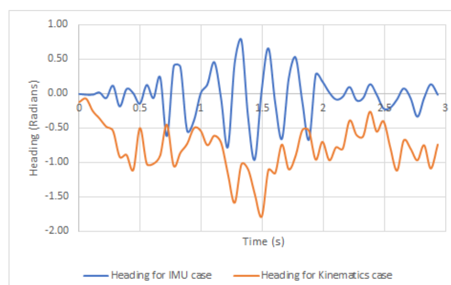

Fig. 4. Heading of straight line performance comparison with and without PID heading control

V. Experiment 2: Control

A. Hardware

Our solution for the slip control system will rely on the linear accelerometer found in the IMU soldered onto Romi's board. We found that, again due to the vibration from the motors, the accelerometer was far too noisy make use of its raw values. We needed to implement a CMA filter to drastically smooth this out. We found that a filter size of 20 gave the best trade-off between reactivity and stability by varying filter size in increments of ten, then comparing the CMA filter output to the raw accelerometer readings to ensure that stimuli were accurately represented in both. We also needed to implement a calibration routine to count for initial bias in the accelerometer's readings. Once we calibrated and filtered our IMU, we plotted its adjusted readings as we started accelerating Romi forward from a standstill, then stopped again after some time. Results are shown in Figure 5. From this figure, we can see that although the IMU lags the kinematics readings, they do produce similar outputs. Therefore, it will be accurate for our implementation as we can simply tune our proportional gain controller accordingly.

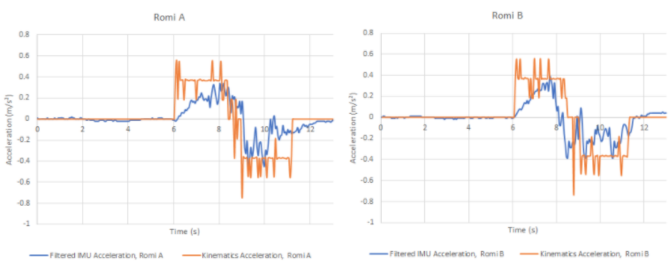

Fig. 5. Acceleration of Romi A and B from IMU Compared to Kinematics as Romi Transitions between Stationary, Accelerating, and Deccelerating Modes.

B. Implementation

1) Base Case: The base case for Experiment 2 will be the improved solution from Experiment 1, such that we achieve straight line trajectory under slip, but with no slip control.

2) Improved solution: To implement slip control, we used a proportional gain controller that utilises an error measurement representing slip. The value of slip is calculated by the discrepancy between the acceleration given by the filtered and calibrated IMU, and the acceleration given by the encoders. We integrate the speed calculated by encoder kinematics to find acceleration of the wheels, and can use the absolute value given by the filtered IMU for its respective rate of acceleration.

We again tuned our controller through trial and error methods, and found that we needed an extremely responsive controller to make any effective difference in wheel slip. We found an optimal proportional gain coefficient of 2500. As with Experiment 1, this parameter would need to be re-tuned if tested on a different surface with a different coefficient of friction.

C. Experiment Methodology

1) Overview of Method: The same test track as with Experiment 1 was used to test our improvements, again with Romi's tires removed. The base case and the improved solution will be sent down the track, again, both repeating the experiment 10 times, with each of their results averaged across the runs.

2) Discussion of Variables:

- **Controlled Variables**: The target acceleration, the method of trajectory control, the test track surface and length, and the Romi used.
- **Independent Variable**: The introduction of slip control via a proportional gain controller as oppose to the base case.
- **Dependent Variable(s)**: The time taken to complete a run of the test track.

3) Discussion of Metric(s): The metric we use to measure the performance of Romi will be the time taken (in seconds) to complete the test track, as average velocity is our main focus of a drag race. We will also, for one example, use both Romis representing each case respectively by setting them up for a drag race. While this method may be more reliable if performed individually, the theatrical opportunity is simply too great to miss.

D. Results

After 10 trials on the 10 meter test track for both the base case and the improved solution, the time taken for each Romi to cross the finish line was averaged, with the results shown below.

Exeriment 2 Results	
Romi Version	Time (s)
Base Case	17.52
Improved Solution	16.55

Once again, we have found an improvement with our updated control system, however in this case, the improvement is small at only 6%. When racing the two cases against one another, we found negligibly small variant in their performance.

VI. Experiment 3: Navigation

We do not need any new hardware for this experiment, so we will just explore implementation and experiment methodology.

A. Implementation

1) Base case: We already have a mechanism from Section (IV.A) to keep track of each wheel's encoder counts that we used to calculate speed via encoder kinematics. In the control loop, a conditional statement was used to check if Romi had reached 10 meters according to the encoders, and to stop the robot if true.

2) Improved solution: To keep track of distance using our Accelerometer, we must twice integrate the IMU's reading with each control loop. Then we can perform a similar check to the base case, but with readings based on the IMU rather than the encoders.

B. Experiment Methodology

1) Overview of Method: Again, we will use a similar test track to Experiments 1 and 2. Again, with each of the cases having 10 runs with their results averaged. We will test both cases running the improved solution from Experiment 1 to ensure slip, and in each case the robot will stop when it detects it is at the end of the test track. The case that is most accurate to the true length of the test track will be the better performer.

2) Discussion of Variables:

- **Controlled Variables**: The target acceleration, the method of trajectory and slip control, the test track surface and length, and the Romi used.
- **Independent Variable**: The method by which we are measuring distance travelled from the start line.
- **Dependent Variable(s)**: The difference (in mm) between the end point of the racetrack as measured by Romi, and the actual racetrack finish.

3) Discussion of Metric(s): Since we are only concerned with Romi's ability to keep track of distance, our performance metric will be the distance (in millimeters) between the end of the test track and the stopping point of Romi. If there is an overshoot, this value will be positive, and negative in the case of an undershoot.

C. Results

Each Romi ran, with heading control but no slip control, down the 10m test track ten times each one stopping when it detects it has reached the finish line: the base case relying on encoder count, and the improved solution relying on IMU readings. The average difference between the real stopping distance, and the target of 10 meters is shown below.

Exeriment 3 Results	
Romi Version	Difference (mm)
Base Case	-3220
Improved Solution	-2650

As expected, we see that the base case greatly undershoots due the encoders picking up rotation of the wheels throughout slip. We see that our solution improved the accuracy of the navigation system by 18%.

VII. Discussion and Conclusion

Our goal was to create a GNC system to make Romi robust in performing drag races. This meant that Romi must stay on the (straight) track for the entire run, Romi must be fast under wheel slip, and Romi must know where the race has ended.

A. Guidance

Our guidance system was where we observed the greatest difference from the base case at 95%. We found that without any form of heading control, Romi's attempt at a straight line trajectory steered wildly off track, as expected due to the asymmetrical slip effects. We found that by combining the reading of a gyroscope and a magnetometer, we are able to achieve heading readings that are not only reliable and without detriment from drift, but also responsive to small variations in rotation. Since our heading readings are reliable, and since our feedback control loop can effectively utilise all proportional, integral and derivative gains, we have been able to show significant improvements to straight line trajectory of our Romi under wheel slip, confirming Hypothesis 1.

B. Control

Our improved control system solution which aimed to maximise acceleration showed improvements over the base case, although the improvements were marginal at just 6%. This is partially due to the inherently small variance in lap times when using equivalent hardware, but also could be due to both hardware and software control issues. The first of which being that we are working with very low coefficients of friction for this experiment due to power limitations, meaning that it is very easy to break the threshold of static friction even at low powers, making effective slip control more difficult. If we had enough power to achieve wheel slip with tyres on, we could potentially show greater improvement. This is because static friction of rubber is relatively high in compared to its dynamic friction, so hindrance of wheel spin will allow for a greater increase in power than when working with solid plastic wheels. We also currently use a simple proportional gain controller for slip, however it may be more effective to gently reintroduce power into the system after wheel slip is detected, rather than a sudden jump. This could again improve power transfer to forward motion. We still have seen some improvement, however, so we can confirm Hypothesis 2.

C. Navigation

While we did see improvements to the navigation system of Romi compared to our base case, our final solution still under performs, suffering from undershoot. This is likely due to the effects of drift on the IMU readings. A suggested improvement in the implemented method may be to intermittently recalculate our bias to mitigate drift and, in turn, create a more reliable system for measuring distance.

Despite the undershoot of the IMU, we still see an improvement over when relying on encoder counts. This is not surprising due the the excessive amount of wheel slip that was observed during these runs. This confirms Hypothesis 3.

D. Future Work

A suggestion for future work is to implement a mechanism to allow Romi to learn the surface that it is on by assessing power and slip, and adjust control behaviour accordingly.

E. Conclusion

We have successfully integrated a GNC system into our Romi for the purposes of drag racing, however some aspects are still in need of improvement. We can firstly state that a launch control system of a vehicle will be more effective when physically scaled up, as the relatively small forces being applied to our system makes wheel slip hard to control. IMUs are also known to be noisy and prone to drift, especially with limited hardware, compromising the reliability of their results. We did, however, confirm all three hypothesis, and have offered a viable solution for a drag racing Romi.

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