1. Introduction

A wheeled Unmanned Ground Vehicle’s (UGV) mobility is a function of the maximum lateral and longitudinal forces that it can apply at the tire/terrain interface. The forces are functions of the vehicle’s geometry, dynamic properties, actuators, and the tire/terrain contact mechanics—properties that are typically fixed. This paper presents the Variable Inertial Vehicle (VIV, see Fig. 1), which has the ability to alter some of the aforementioned properties during locomotion [1]. More specifically, the VIV can change its center-of-mass location during operation and thus dynamically control the normal forces that act on the front and rear tires. Since a tire’s longitudinal and lateral forces are strongly related to the tire’s normal force [2], the VIV is able to modify its dynamics to suit a particular situation. For example, the VIV can load its driven wheels to achieve better acceleration or load its steered wheels to achieve high sideslip angle trajectories. This allows the VIV to travel at a high average speed, quickly alter its trajectory to avoid obstacles, and operate more efficiently on deformable terrain.

The effect is created through a mechanism that shifts the VIV’s high-density batteries along a central corridor running the length of the vehicle. The VIV shifts a 14 [kg] mass 0.8 [m] in 1.2 [s] using 54 [J] of energy. This is less than 0.003% of the total energy available to the system and does not affect mission duration. Furthermore, the mass would only be shifted that entire length when the vehicle needs to quickly recover from unwanted sideslip or execute a highly dynamic turn (e.g. to avoid an obstacle detected at short range) [3].

Part of the motivation behind the design of the VIV comes from professional rally car drivers, who achieve similar vehicle dynamics when driving on loose surfaces. For example, to execute a drifting maneuver they first actuate the brakes to pitch the vehicle forward and transfer weight to the front wheels. The brake is then released and the front wheels are steered hard into a turn. The driver then applies a small amount of power to the rear wheels, causing them to develop excessive wheel slip and subsequently allowing the vehicle to experience oversteer.

The VIV achieves similar results by directly changing its center-of-mass location instead of relying on braking or acceleration forces. This method allows for drifting maneuvers to be executed more reliably and with greater control. It also allows for high yaw rates, which provide quick heading changes. This can be very useful for high speed vehicles to navigate tight environments or avoid obstacles. Furthermore, with the shifting mass on the rear of the VIV, greater acceleration is achievable on both rigid and deformable terrains.

2. Vehicle Description

The VIV is designed to be man-portable and battery-powered. Its parameters are shown in Table 1. The vehicle is front-wheel steered and rear-wheel driven. The primary design objective was to maximize the difference in mass distribution with the shifting mass at the rear and the front of the vehicle. This is accomplished by constructing the shifting mass out of high-density components that are not part of the drive train. As designed, the system can shift its mass in 1.2 [s] for a total mass distribution change of 38.2%.

The VIV’s chassis has a corridor that allows for the shifting mass to travel a length greater than the vehicle’s wheelbase (see Fig. 2). To make this possible, the chassis has no internal crossbracing, which requires careful design to ensure that the vehicle has sufficient...
torsional stiffness. Furthermore, components such as the steering and suspension system are located outside of the corridor. To accommodate this, the VIV employs a mono-shock suspension for both the front and rear tires, and the front wheels are steered using individual actuators to avoid the need for complex mechanical linkages.

The arrangement of the fixed components (e.g. chassis, suspension, powertrain, steering, central computer, and GPS) was carefully determined to place the fixed center-of-mass (COM$_f$) as close as possible to the center of the VIV’s wheelbase. This gives the shifting mass equal effect upon both the front and rear weight distribution ratios (see Fig. 3). With the center-of-mass of the fixed portion of the vehicle at the geometric center of the wheelbase, the calculation of the rear weight distribution ratio based on the shifting mass position was simplified, and is given as:

$$W_r = \frac{1}{2} - \frac{l_s m_s}{L m}$$  \hspace{1cm} (1)

where $W_r$ is the rear weight distribution ratio, $l_s$ is the shifting mass position, $m_s$ is the mass of the shifting mass element, $m$ is the total vehicle mass and $L$ is the wheelbase.

Figure 4 shows a contour plot of the weight distribution as a function of the shifting mass position and the ratio of the shifting mass to total mass. Based on our design requirements, the VIV needs to follow or exceed the 0.25 and 0.75 weight distribution ratio contour lines. Note that at higher mass ratios it is more effective to increase the overall shift distance

![The VIV](image1.png)

(a) The VIV on deformable terrain

![CAD rendering of the VIV](image2.png)

(b) CAD rendering of the VIV

Fig. 1 The VIV

![CAD rendering of the front of the VIV](image3.png)

Fig. 2 CAD rendering of the front of the VIV with the internal shifting mass and end plates removed to illustrate the shifting mass corridor

![Illustration of the shifting mass COM$_S$, fixed chassis COM$_f$ and resultant vehicle COM$_V$](image4.png)

Fig. 3 Illustration of the shifting mass COM$_S$, fixed chassis COM$_f$ and resultant vehicle COM$_V$

![Contour plot showing the rear weight distribution ratio across a range of shift distances and mass ratios](image5.png)

Fig. 4 Contour plot showing the rear weight distribution ratio across a range of shift distances and mass ratios. Note that at higher mass ratios it is more effective to increase the overall shift distance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Total Mass</td>
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<tr>
<td>Shifting Mass</td>
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<tr>
<td>Mass Distribution</td>
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<tr>
<td>Wheelbase</td>
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<tr>
<td>Track Width</td>
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<td>Max Shifting Mass Travel</td>
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<td>Shifting Mass Speed</td>
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<tr>
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<tr>
<td>Maximum Speed</td>
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<tr>
<td>Maximum Acceleration</td>
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</tbody>
</table>

Table 1 Robot parameters
The VIV: A Mobile Ground Robot with Variable Inertial Properties

3. Experimental Results

Fig. 5 (a) shows the VIV executing two hairpin turns with its c.o.m. in different locations. To execute this maneuver, the VIV accelerates in a straight line up to 6 [m/s]. At that point, depending on the trial, the VIV either shifts its mass forward or keeps it at the back. The front wheels are then turned to obtain a 30° Ackermann steering angle. Note the extremely large sideslip angles, \( \beta \), experienced by the VIV during these turns, especially when the mass is shifted to the front. The sideslip angle is defined as the angle between heading vector and velocity vector. To the authors’ knowledge no other UGV has demonstrated such large values of sideslip during a controlled maneuver. This ability provides the VIV with increased obstacle avoidance capabilities. Furthermore, the high sideslip angle allows the VIV to maintain its speed throughout the maneuver.

Fig. 5 (b) illustrates the sideslip angle as a function time. Note that when the mass is on the front the sideslip exceeds 50°, 20° degrees more than when the mass is located on the rear.

4. Conclusion

This paper presented a novel UGV with the ability to control the normal force acting over either its front or rear wheels by shifting a mass longitudinally along its wheelbase. A description of the vehicle’s shifting mass mechanism highlighted aspects of the UGV that differed from more traditional designs. Experimental results briefly demonstrated the robot’s ability to execute non-kinematically feasible paths. Future work in this area focuses on control algorithms that account for this unique feature.

References

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