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An Analysis of Rollover Stability Measurement for High-Speed Mobile Robots

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Abstract – **Mobile robots and passenger vehicles are frequently required to operate at high speeds, on terrain that is sloped or uneven. These systems can be susceptible to rollover, particularly during severe maneuvers. This paper presents an analysis of rollover stability measurement for mobile robots operating at high speeds. The analysis examines the accuracy of a commonly accepted rollover stability metric during operation on sloped and rough terrain. The effects of sensor placement, center-of-gravity position estimation error, and wheel dynamics are examined. It is shown that these effects can have a significant impact on stability measurement during high speed operation.**

Index Terms – Mobile Robots, Sensing, Navigation, Rollover, Stability

I. Introduction and Description of Previous Research

Navigation of high-speed mobile robots has received a significant amount of recent research activity, highlighted by the interest in DARPA's Grand Challenge autonomous vehicle race [1]. Applications of high-speed robots include exploration, reconnaissance, and material delivery. These systems are designed to operate on natural terrain that may be sloped, slippery, deformable, and uneven. Unfortunately, these systems are susceptible to rollover, particularly while performing severe maneuvers. Despite the fact that many systems are designed with rugged chassis (and some are designed to be invertible), rollover accidents often disable the robot and/or damage its payload. Rollover accidents have been reported in the literature and have been experienced by this paper's authors during field experiments.

The danger of rollover accidents is even more significant in passenger vehicles, as rollovers result in more than 9,000 fatalities and 200,000 non-fatal injuries in the United States annually, with a fatality rate second only to frontal collisions [2]. As a result, significant research has been devoted to detecting and preventing rollover accidents in passenger vehicles [4, 5]. Despite these efforts, detection and prevention of rollover remains an important challenge.

Previous researchers in the automotive industry have developed numerous metrics to quantify rollover stability. These metrics usually assume that the vehicle is operating on smooth, level terrain. A simple but useful metric is the Static Stability Factor (SSF), which is computed as the ratio of the lateral position of the vehicle center-of-gravity (c.g.) to the vertical position (see (1) and Fig. 1). Larger values of SSF indicate greater stability. Physically, the SSF corresponds to the lateral acceleration in g's that causes wheel lift-off for a rigid vehicle traversing flat ground [3]. It has been shown, however, that wheel lift-off can occur at lateral accelerations smaller than the SSF [3]. Adjustments to the SSF to account for suspension kinematics and tire compliance were described in [3]. This metric does not consider the effects of terrain inclination, which leads to error in the estimate of critical lateral acceleration when a vehicle maneuvers on slopes.

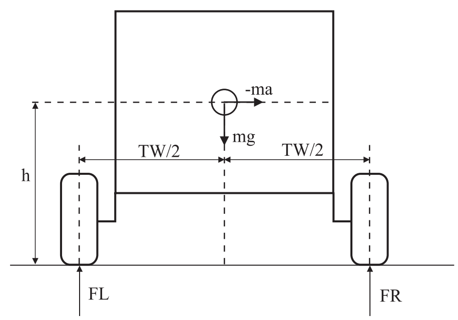

Figure 1: Static Stability Factor diagram

$$SSF = TW/2h \qquad (1)$$

A family of metrics termed "load transfer metrics" estimates the difference in tire normal forces acting on each side of the vehicle. Such a metric can indicate the nearness to wheel lift-off on smooth terrain. A simple form of such a metric is shown in (2). Another formulation is presented in [4]. Other researchers have employed similar metrics (along with a forward-dynamic vehicle model) to estimate the time before a rollover event might occur [5]. A disadvantage of load transfer metrics is that they detect wheel lift-off, which is a necessary but not a sufficient condition for rollover. Traversing a pot-hole, curb, or uneven terrain often causes loss of ground contact without leading to rollover.

$$R = (FL - FR)/(FL + FR) \qquad (2)$$

Other research in rollover stability measurement has been performed by researchers in the robotics community. Typically this work has analyzed the stability of low-speed robots operating on uneven terrain. Early work focused on the static stability of legged robots. A metric was developed describing the minimum difference in potential energy between a given vehicle state and the vehicle state at rollover, known as the Energy Stability Margin [6]. Subsequent work considered the total work required to bring the robot to a rollover state [7]. A similar energy-based metric was also developed in the automotive industry [8].

A general metric for dynamic robot stability, termed the force-angle stability metric, was proposed in [9]. This metric can be applied to robots of arbitrary configuration, such as mobile manipulators or planetary rovers with many wheels. This metric has been applied to a number of scenarios, including Mars rovers [10], forestry vehicles with large manipulators [9], and a tall forklift [11]. This metric is generally considered the state-of-the-art in stability measurement due to its flexibility and theoretical accuracy.

In this paper we analyze the application of a modified form of the metric in [9] to robots moving at high speeds in various terrain conditions. In Section II, the modified metric is reviewed and its physical meaning is interpreted. In Section III, an analysis of the effects of sensor placement, c.g. position estimation error, and wheel dynamics are studied. It is shown that these effects can have a significant impact on stability measurement during high speed operation, and should be considered during practical implementation.

II. Metric Presentation and Interpretation

In this section a modified form of the force-angle stability metric is presented, with application to a four-wheeled robot representative of common high-speed manned and unmanned ground vehicles. A physical interpretation of the metric is then presented.

A. Metric Formulation

In this section the metric of [9] is presented, here formulated as a ratio of moments rather than a stability angle. In this approach, the robot's l wheel-terrain contact points $\mathbf{p}_i$, $i=\{1,\ldots,l\}$ are numbered in ascending order in a clockwise manner when viewed from above, as shown in Fig. 2. These points form the nodes of a three-dimensional support polygon. The lines joining the wheel-terrain contact points are referred to as tipover axes and are denoted $\mathbf{r}_i$. They are computed in a frame {XYZ} fixed at an arbitrary point on the robot body, as:

$$\mathbf{r}_i = \mathbf{p}_{i+1} - \mathbf{p}_i,\ \ i = \{1,\ldots, l\text{-}1\} \tag{3}$$

$$\mathbf{r}_l = \mathbf{p}_1 - \mathbf{p}_l \tag{4}$$

The forces and moments acting on a robot can be separated into three categories: l support forces $\mathbf{F}_i$ acting at the wheel-terrain contact points $\mathbf{p}_i$, k non-support body forces $\mathbf{B}_j$, $j=\{1,\ldots,k\}$, acting at points $\mathbf{q}_j$, and d'Alembert's force $-m\mathbf{a}_c$, acting at $\mathbf{c}$, the vehicle c.g. The non-support body forces include gravity and disturbance forces caused by aerodynamic drag, reactions from manipulation or trailers, or body collisions (see Fig. 3). Note that suspension forces are internal to the system and can be ignored in this metric.

We choose as a metric the moments caused by body forces and d'Alembert's force computed with respect to the i^{th} tipover axis, as:

$$SM_i = \sum_{j=1}^{k}\left(\left(\mathbf{q}_j - \mathbf{p}_i\right)\times \mathbf{B}_j\right)\cdot \mathbf{r}_i - \left(\left(\mathbf{c}-\mathbf{p}_i\right)\times m\mathbf{a}_c\right)\cdot \mathbf{r}_i \tag{5}$$

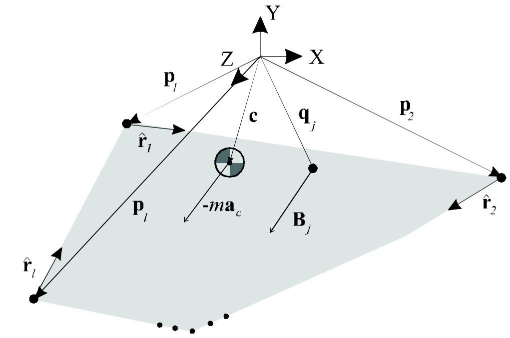

Figure 2: Support polygon for general robot

These moments can be normalized by the minimum static moment on flat ground, denoted SM_0. The metric is then chosen as the minimum moment over all tipover axes:

$$\alpha = \min_i\left(SM_i / SM_0\right) \tag{6}$$

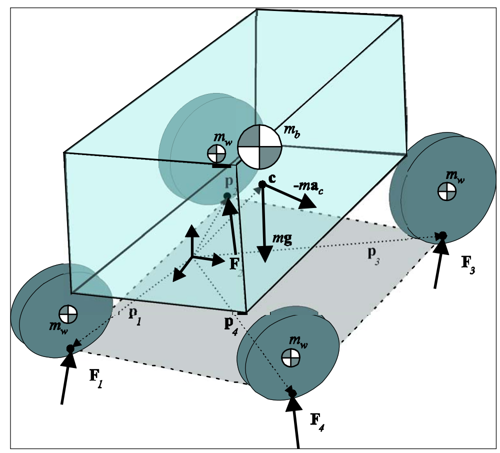

Figure 3: Free-body diagram for nominal high-speed robot

B. Application to Nominal High-Speed Ground Vehicle

In practice, many high speed ground vehicles resemble passenger vehicles in that they possess four wheels of non-negligible mass mounted to a robot body via a suspension. Thus the vehicle can be modeled as a main body of mass m_b and c.g. position $\mathbf{b}$, connected to four wheels of equal mass m_w and c.g. positions $\mathbf{w}_i$. The total vehicle mass is $m=m_b+4m_w$. In this case l=4 and the support polygon is quadrilateral, though possibly non-planar if suspension travel is significant. For the nominal case we also assume that the gravitational force $\mathbf{B}_1=m\mathbf{g}$ acting at the c.g. is the only non-support force.

For these nominal systems, suspension effects can influence vehicle stability in several ways. First, a change in suspension configuration will lead to a change in the position in the overall system c.g. The location of the instantaneous c.g. of the vehicle $\mathbf{c}$ can be computed as:

$$\mathbf{c} = \mathbf{b} + \frac{1}{m}\sum_{i=1}^{l} m_w\left(\mathbf{w}_i - \mathbf{b}\right) \tag{7}$$

where the vectors $\mathbf{w}_i$ are functions of the suspension configuration. Suspension displacement also changes the orientations of the tipover axes $\mathbf{r}_i$. The effect of these phenomena on stability measurement will be analyzed in Section III.

Suspension dynamics can also affect the system c.g. acceleration. This can be observed by differentiating (7) twice with respect to an inertial frame. The lumped system c.g. acceleration $\mathbf{a}_c$ is computed as:

$$\mathbf{a}_c = \mathbf{a}_b + \frac{1}{m}\sum_{i=1}^{l} m_w\left(\ddot{\mathbf{w}}_i + 2\boldsymbol{\omega}\times\dot{\mathbf{w}}_i + \dot{\boldsymbol{\omega}}\times(\mathbf{w}_i - \mathbf{b}) + \boldsymbol{\omega}\times(\boldsymbol{\omega}\times(\mathbf{w}_i - \mathbf{b}))\right) \quad (8)$$

Note that is the angular velocity in a body-fixed frame. This equation requires measurement of the acceleration of the vehicle body at **b** in addition to several terms related to wheel dynamics. This effect will also be studied in Section III.

Another factor than can influence stability measurement of high-speed systems is uncertainty in the computation of the vectors $\mathbf{p}_i$ (i.e. the locations of the wheel-terrain contact force). This is due to the fact that systems with deformable wheels and/or deformable terrain exhibit pressure distributions at the wheel-terrain contact interfaces, rather than point forces (see Fig. 4). This pressure distribution can be represented by a single force at the center-of-pressure; however the form of the distribution can vary with changes in wheel orientation, terrain profile, or wheel load. The effect of uncertainty in the location of the wheel-terrain contact force on stability measurement will be studied in Section III.

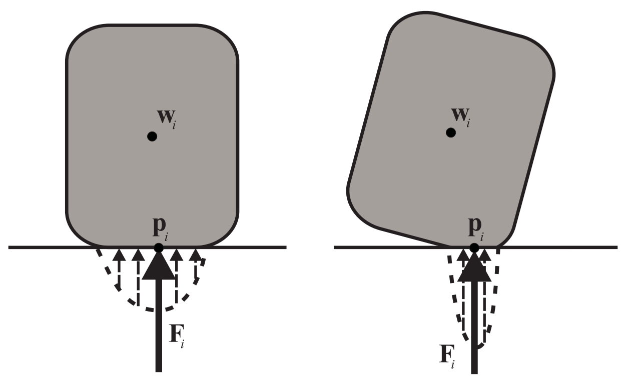

Figure 4: Illustration of tire force location as a function of wheel orientation

For the high-speed vehicles considered here the c.g. is usually significantly closer to the lateral tipover axes than the front and rear, and thus "pitchover" about the front or rear tipover axes is uncommon. The nominal stability metric can thus be computed as the smaller of the moments about the left and right rollover axes. Choosing *i*=1 as the right-front wheel, this results in:

$$SM_i = \left((\mathbf{c} - \mathbf{p}_i)\times m(\mathbf{g} - \mathbf{a}_c)\right)\cdot \mathbf{r}_i \quad (9)$$

$$\alpha = \min\{(SM_1/SM_0),(SM_3/SM_0)\} \quad (10)$$

B. Physical Interpretation of Metric

The metric as presented in (9) can be interpreted as a computation of the net moments due to body forces about each potential rollover axis. The metric can also be analyzed from the perspective of angular momentum. Applying the angular momentum principle about axis *i* yields:

$$\mathbf{M}_i \cdot \mathbf{r}_i = \dot{\mathbf{H}}_i \cdot \mathbf{r}_i \quad (11)$$

where moments are caused by both support forces and body forces (not including d'Alembert's force), as:

$$\mathbf{M}_i = \sum_{j=1}^{k}\left((\mathbf{q}_j - \mathbf{p}_i)\times \mathbf{B}_j\right) + \sum_{j=1}^{l}\left((\mathbf{p}_j - \mathbf{p}_i)\times \mathbf{F}_j\right) \quad (12)$$

Denoting $\mathbf{I}_b$ as the moment of inertia about the body c.g. and $\mathbf{v}_c$ as the velocity of the c.g. with respect to an inertial frame, the angular momentum can be written as:

$$\mathbf{H}_i = \mathbf{I}_b\boldsymbol{\omega} + (\mathbf{c} - \mathbf{p}_i)\times m\mathbf{v}_c \quad (13)$$

Taking a time derivative yields:

$$\begin{aligned}\dot{\mathbf{H}}_i = \mathbf{I}_b\dot{\boldsymbol{\omega}} + \boldsymbol{\omega}\times(\mathbf{I}_b\boldsymbol{\omega}) + (\mathbf{c} - \mathbf{p}_i)\times m\mathbf{a}_c +\\ (\dot{\mathbf{c}} - \dot{\mathbf{p}}_i + \boldsymbol{\omega}\times(\mathbf{c} - \mathbf{p}_i))\times m\mathbf{v}_c\end{aligned} \quad (14)$$

or

$$\dot{\mathbf{H}}_i = \dot{\mathbf{H}}_i^* + (\mathbf{c} - \mathbf{p}_i)\times m\mathbf{a}_c$$

where $\dot{\mathbf{H}}_i^* = \mathbf{I}_b\dot{\boldsymbol{\omega}} + \boldsymbol{\omega}\times(\mathbf{I}_b\boldsymbol{\omega}) + (\dot{\mathbf{c}} - \dot{\mathbf{p}}_i + \boldsymbol{\omega}\times(\mathbf{c} - \mathbf{p}_i))\times m\mathbf{v}_c$.

After some manipulation (11) can be written as:

$$\begin{aligned}&\sum_{j=1}^{k}\left((\mathbf{q}_j - \mathbf{p}_i)\times \mathbf{B}_j\right)\cdot \mathbf{r}_i - \left((\mathbf{c} - \mathbf{p}_i)\times m\mathbf{a}_c\right)\cdot \mathbf{r}_i\\ &= \dot{\mathbf{H}}_i^*\cdot \mathbf{r}_i - \sum_{j=1}^{l}\left((\mathbf{p}_j - \mathbf{p}_i)\times \mathbf{F}_j\right)\cdot \mathbf{r}_i\end{aligned} \quad (15)$$

The tipover stability metric can then be expressed as:

$$SM_i = \dot{\mathbf{H}}_i^*\cdot \mathbf{r}_i - \sum_{j=1}^{l}\left((\mathbf{p}_j - \mathbf{p}_i)\times \mathbf{F}_j\right)\cdot \mathbf{r}_i \quad (16)$$

This form of the metric can be interpreted as follows: If we assume that robot support forces are pure forces acting only positively (i.e. they cannot "pull" the vehicle toward the ground) it can be shown that their contribution in (16) is always positive. This implies that negative values of the metric are caused by the angular momentum terms resulting from non-support forces. Thus (16) explicitly shows that wheel-terrain support forces are always stabilizing and loss of stability is always due to dynamic effects of vehicle motion.

Note that a negative metric value does not guarantee that rollover will occur, but rather indicates that the vehicle is being instantaneously subjected to a destabilizing moment. Conversely, a positive metric implies that the vehicle is either stably positioned on the terrain without any wheel lift-off, or that it is decelerating from a lift-off. It should be noted that for the nominal vehicle, ballistic motion will cause the metric to be zero about all axes.

III. Analysis of Rollover Stability Measurement for High-Speed Maneuvers

In this section the sensitivity of the metric presented in Section II to various real-world effects is studied. These effects include the sensor placement location, c.g. position estimate, tire force location estimate, and wheel mass effects.

A. Analysis Description

A model of a generic high-speed robot was developed in the commercial multibody dynamic simulation software package ADAMS. Critical vehicle parameters are listed in Table 1. Vehicle stability was measured during a representative aggressive maneuver on various terrains. An example stability metric time history during a maneuver is shown in Fig. 5. The metric value starts at 1.0 during straight-line driving on flat terrain, then dips below 0.4 during high-acceleration elements of the maneuver.

TABLE I
Nominal Vehicle Parameters

Body mass	2160 kg
Single wheel mass	112 kg
Wheelbase	2850 mm
Track width	1620 mm
C.G. height from ground	900 mm
Suspension travel	200 mm
Unloaded wheel radius	395 mm

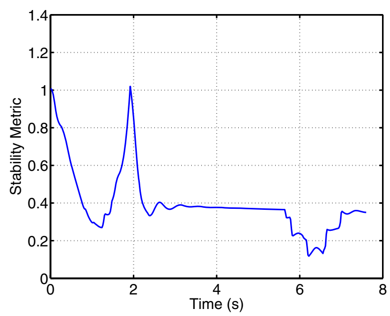

Figure 5: Example of stability metric time history during aggressive maneuver

Metric accuracy was studied during execution of a representative aggressive maneuver known as a fish hook (see Fig. 6). This maneuver is composed of an open-loop steering input of a 60 degree step in one direction, followed by a 240 degree step in the opposite direction, as shown in Fig. 7. This maneuver is used in governmental rollover safety tests due to its aggressiveness [12]. In the following analysis the vehicle's initial speed was 100 km/hr, which corresponds to 9.75 body lengths/sec. A simple velocity control loop was used to regulate the speed near the initial value during maneuvers.

Maneuvers were executed on terrain with an inclination of 8º about the vehicle roll axis (i.e. a side-slope). The terrain roughness ranged from smooth to very rough, with roughness generated as Gaussian variation in terrain elevation superimposed on a smooth plane. Three levels of roughness were generated with elevation variances of 20, 60, and 100 mm^2. Multiple terrain meshes were generated and tested for each specified variance to account for randomness in the terrain generation method.

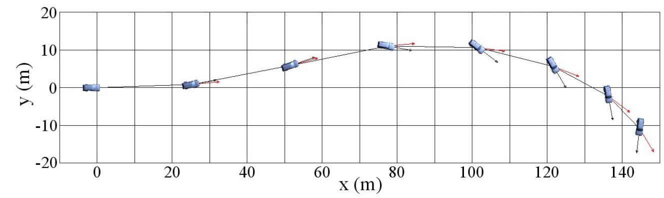

Figure 6: Fish hook vehicle path

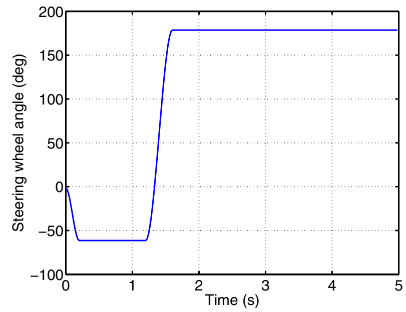

Figure 7: Fish hook steering input

In the following analysis, the stability metric was computed for several trials over various terrain conditions. A "ground truth" metric was formed by computing the metric value based on exact simulation parameters. Error data presented in the following sections was then computed as a difference between the ground truth and an erroneous metric that was computed under various real-world approximations.

B. Sensitivity to sensor placement

The metric presented above assumes that the vector difference of gravity and acceleration at the vehicle c.g. can be measured or estimated. Disambiguating gravitational and acceleration vectors from an accelerometer output is challenging in dynamic situations, however this difficulty can be avoided by simply combining the terms for gravitational and inertial forces in (5) (or (9)) and then measuring the net gravitational/inertial force.

Accurate measurement of this net force, however, is challenging in itself. Assuming the robot c.g. position is known, accurate measurement of chassis acceleration necessitates either placement of the sensor at the robot c.g., or transformation of the sensor output to account for the difference in position between the sensor position and the c.g. position. Since it is often impractical to place a sensor at the robot c.g. (and the c.g. position is rarely known precisely), a transformation must be employed. For a sensor located at some position **s**, the transformation of sensor output to the c.g. location is given by (17). Use of (17) requires knowledge of the robot angular velocity and angular acceleration.

$$\mathbf{a}_c - \mathbf{a}_s = \dot{\boldsymbol{\omega}} \times (\mathbf{c} - \mathbf{s}) + \boldsymbol{\omega} \times (\boldsymbol{\omega} \times (\mathbf{c} - \mathbf{s})) \quad (17)$$

In practice the sensor acceleration is often assumed to be equal to the c.g. acceleration, giving rise to metric error. Since for many vehicles a convenient sensor location may be substantially distant from the c.g. location, it was hypothesized that this could lead to significant metric error.

Stability metric accuracy was studied for the representative vehicle performing a fish hook maneuver on various terrain roughnesses, with sensor placement offsets of 50% of the vehicle width from the c.g. and no transformation applied. For each terrain roughness 10 simulation trials were run. RMS errors of the normalized metric (10) over the time history of each trial are summarized in Table II.

TABLE II
METRIC ERROR DUE TO SENSOR PLACEMENT

Terrain Height Variance (mm^2)	Mean RMS Error	St. Dev. RMS Error
0	6.58E-06	0.00E+00
20	8.84E-06	5.48E-07
60	1.75E-05	1.67E-06
100	2.43E-05	3.14E-06

It was observed that sensor placement error did not lead to significant error. This suggests that for the class of systems considered here, robot body acceleration can be measured adequately from an IMU mounted rigidly at a convenient location on the robot chassis.

C. Sensitivity to uncertainty in center-of-gravity position and wheel-terrain contact force location

As noted above, a robot's c.g. position is rarely known precisely, and can change due to variations in loading, addition of payloads, fuel consumption, and changes in suspension configuration. On-line estimators of c.g. location have been developed [13, 14], however it is likely that errors in stability measurement due to incorrect estimates of c.g. location will occur in practice. It should be noted that errors in c.g. location cause error in the vector $\mathbf{c}\text{-}\mathbf{p}_i$ in (5). Since $\mathbf{p}_i$ describes the relative location of the c.g. and a tipover axis, additional error is caused by uncertainty in wheel-terrain contact force location, as discussed in Section IIB.

Stability metric accuracy was studied for the representative vehicle performing a fish hook maneuver on various terrain roughnesses, with errors in the length of the vector $\mathbf{p}_i$ chosen as 15% of the true c.g. height from the ground. For each terrain roughness 10 simulation trials were run. RMS errors of the normalized metric (10) over the time history of each trial are summarized in Table III.

TABLE III
METRIC ERROR DUE TO ERROR IN C.G. HEIGHT

Terrain Height Variance (mm^2)	Mean RMS Error	St. Dev. RMS Error
0	0.085	0.00E+00
20	0.084	1.74E-04
60	0.080	1.55E-03
100	0.074	2.47E-03

It was observed that errors in the estimation of c.g. position and wheel-terrain contact force location led to small but significant errors on all terrains. Since the value of the stability metric is 1.0 when a robot is at rest on flat terrain, a mean error of 0.085 on smooth terrain can be interpreted as a nearly 10% metric error. Further, for many real-world applications, c.g. position estimate error may greatly exceed 15%. This suggests that for the class of systems considered here, c.g. position estimation is a significant factor for dynamic rollover stability measurement.

D. Sensitivity to wheel mass effects

As described in Section IIB, changes in suspension configuration may significantly change the lumped vehicle c.g. position if the wheel masses represent a significant percentage of the total vehicle mass. Additionally, wheel dynamics may influence the lumped vehicle acceleration.

Stability metric accuracy was studied for the representative vehicle performing a fish hook maneuver on various terrain roughnesses, with the effects of suspension configuration changes and wheel dynamics ignored (i.e. the stability metric was computed using constant parameters equal to those taken while the robot was at rest on flat ground). Recall that the wheel mass represents 17% of the total robot mass. For each terrain roughness 10 simulation trials were run. RMS errors of the normalized metric (10) over the time history of each trial are summarized in Tables IV and V.

TABLE IV
METRIC ERROR DUE TO CHANGES IN SUSPENSION CONFIGURATION

Terrain Height Variance (mm^2)	Mean RMS Error	St. Dev. RMS Error
0	0.056	0.00E+00
20	0.055	1.14E-04
60	0.052	1.02E-03
100	0.046	6.82E-03

TABLE V
METRIC ERROR DUE TO WHEEL DYNAMIC EFFECTS

Terrain Height Variance (mm^2)	Mean RMS Error	St. Dev. RMS Error
0	0.020	0.00E+00
20	0.068	1.06E-02
60	0.187	8.43E-03
100	0.282	3.57E-02

It was observed that errors due to both changes suspension configuration and wheel dynamic effects led to potentially significant errors. Error due to wheel dynamic effects increased with increasing terrain roughness to a mean RMS value of nearly 30% of the flat-ground metric value. This suggests that for the class of systems considered here, both changes in suspension configuration and wheel dynamic effects are significant factors for dynamic rollover stability measurement.

E. Application to Experimental Data

The stability metric presented above was applied to data collected on a high-speed mobile robot during outdoor experiments. The robot, ARTEMIS, is shown in Fig. 8. ARTEMIS is equipped with a Zenoah G2D70 gasoline engine, 700 MHz Pentium III PC-104 computer, Crossbow AHRS-400 INS, a tachometer to measure wheel angular velocity, 20 cm resolution DGPS, and Futaba steering and throttle control servos. The robot dimensions are 0.89 x 0.61 x 0.38 m.

Three rollover experiments were conducted on a flat field covered with artificial turf. In each experiment ARTEMIS was commanded to follow a path of progressively increasing curvature at speeds ranging from 5.0 to 8.0 m/s. Stability was monitored using a "ground truth" formulation of (10) using parameters derived from careful parameter identification experiments [15]. This was compared to a formulation of (10) relying on estimates of c.g. position based on engineering judgment and coarse measurements. This estimate was found to represent a 15.5% difference from the ground truth value.

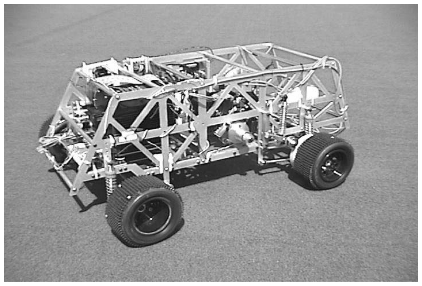

Figure 8: ARTEMIS High-speed mobile robot

A representative experimental result can be seen in Fig. 9. In this maneuver ARTEMIS began to roll over at t=7.5 s, however the estimated metric incorrectly predicted that the vehicle remained stable. (Note that complete rollover was prevented by mechanical outriggers.) The ground truth metric, relying on accurate parameter estimates, correctly indicated rollover by falling below zero. This result highlights the importance of accurate c.g. position estimation during high speed stability measurement.

Table VI summarizes the results from all three trials. For each trial the minimum stability metric is presented for the ground truth and the estimated metric. It can be seen that the ground truth correctly predicted rollover in all cases, whereas the estimated metric was incorrect in one of the three trials.

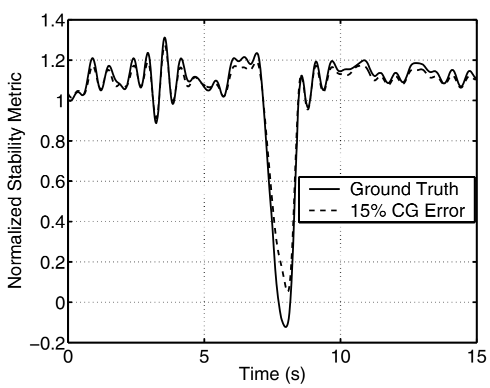

Figure 9: Comparison of experimental stability measurement data

TABLE VI
EXPERIMENTAL METRIC ERROR

Experimenta l Trial No.	Minimum Metric Value (Ground Truth)	Minimum Metric Value (Estimated)	Rollover?
1	-0.511	-0.300	Yes
2	-0.123	0.051	Yes
3	-0.228	-0.006	Yes

IV. CONCLUSION

This paper has presented analysis of rollover stability measurement for high-speed mobile robots. Various real-world factors that influence stability metric measurement accuracy were studied, including the effects of sensor placement location, c.g. position estimate, tire force location estimate, and wheel mass effects. Fig. 10 shows a plot of the errors due to the various effects considered here as a function of terrain roughness.

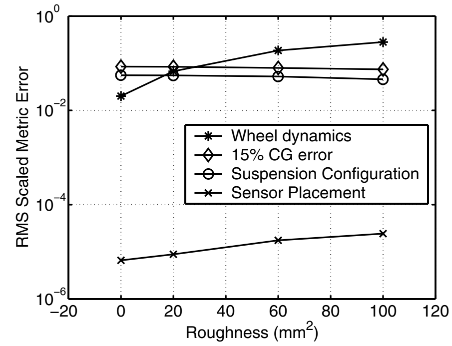

Figure 10: Errors in stability measurement due to various effects

From Fig. 10 and Tables I-V it can be seen that for the class of systems considered here, sensor placement does not have a significant effect on stability measurement accuracy. The other effects considered here, however, do have a significant effect and should be considered during measurement of high-speed robot stability.

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