Wheel Load Transfer in High-Speed Unmanned Vehicles

John R. Rogers, United States Military Academy, West Point, NY, USA, john.rogers@usma.edu

Abstract—A low-cost unmanned vehicle design is presented as a tool to explore autonomous high-speed performance. The vehicle is based on a 1/10 scale radio control model four-wheel-drive truck. The transfer of vertical loads from wheel-to-wheel is proposed as a parameter to control drifting. A means of estimating wheel loading from suspension displacement is presented.

1 INTRODUCTION

Portable Unmanned Ground Vehicles (UGVs) are useful for military tasks including equipment transport, reconnaissance, surveillance, target acquisition, mine detection, urban operations and others. Current systems protect and aid the Soldier to accomplish his mission, but they are generally expensive and complicated to design, manufacture, and operate. To investigate an alternative solution, a program to demonstrate the capabilities of a low-cost high speed small UGV was initiated in the spring of 2008 at the United States Military Academy (USMA). The long term vision inspiring the USMA program is to have UGVs with autonomous performance approaching that of full-sized vehicles under the control of expert human drivers. While it is not realistic to expect human-like autonomous control in the near future, the vision guides the day-to-day decisions of the project. A natural first step is to observe expert driving and explore how to mimic it autonomously. The near-term goals of this program are to:

- establish benchmark performance for simple high-speed maneuvers under human control,
- log driver inputs and vehicle response for these maneuvers
- “play back” the driver inputs to the vehicle autonomously (open loop), and
- explore options for feedback to advance high-speed autonomy

The USMA project is limited to small, four-wheeled vehicles. For the purpose of this paper a “small” UGV is on the order of 10 kilograms, small enough to be carried by one man. Four-wheeled vehicles have the advantages of high speed and off-the-shelf components. The Joint Robotics Program office lists the following priorities in their 2005 Master Plan [1]: man-transportable robotic system development (priority 1), increased autonomy (priority 3), and disposable robot technology (priority 9). High-speed operations are also a priority. It is hoped that the current work will contribute in these areas.

The technical approach will be to embed low-cost off-the-shelf microcontrollers in off-the-shelf four-wheeled vehicles, and exercise, measure, and improve them. The results are expected to advance autonomy in small high-speed, low-cost, man portable UGVs for military applications. It is hoped that the insight gained from studying small vehicles will scale up to benefit the development of larger UGVs.

There are two primary challenges with small autonomous vehicles. The first is dealing with the weight constraint: sensors and computers are heavy relative to the vehicle. The second challenge is dealing with the time scale. It is common for vehicles as small as 10 kilograms to travel at 30 car-lengths per second. At this rate, a 15-foot long car would be travelling at 300 miles per hour. The processing speed of a small UGV controller must be uncompromisingly fast in order to follow a path or avoid obstacles at this velocity.

Other considerations include the degree of autonomy which is based on the amount, type, and quality of the sensors used, the computing power of the controller, and the sophistication of the algorithm. The UGV’s maneuverability is determined by the steering
configuration, suspension and tire choice, and weight placement. The UGV’s range is determined by weight, fuel or battery consumption, and mission requirements.

This paper reports on progress of the USMA UGV project. The E-Maxx four-wheeled radio-controlled vehicle manufactured by Traxxas, Fig. 1, was identified as a small, low-cost, high-speed robotic platform that fits well in the academic environment at USMA. This platform is being used in the development of an autonomous system for research; the same system is used in a complementary class project.

2 BACKGROUND

Several references regarding small vehicle high speed autonomy and performance document the state of the art. Philpott [2], Quigley [3], and Rogers [4] describe the accomplishments of years one and two of a three year program to develop an autonomous vehicle program at the United States Military Academy; this paper is a continuation of that effort. Tsiotiris and Overholt [5] used a two-wheel automobile model in their cornering simulation to show that the “pendulum turn” is the optimal technique to maximize exit velocity from a 90° cornering maneuver. Using maximum exit velocity as a performance measure compares favorably to minimum time through the course. Spenko [6] describes a method to avoid obstacles and re-plan a path at high speed. His analysis uses the concept of mapping obstacles as well as vehicle limits such as roll over and sideslip on the “trajectory space” plane of velocity and path curvature.

Bruch [7] discusses the difficulty in integrating autonomy procedures of large UGVs into smaller platforms. The constraining factors, sensors and power requirements, increase size and weight of the UGV and decrease its performance. Therefore new procedures are required. SSC San Diego’s autonomy program includes the development of GPS waypoint navigation and obstacle avoidance. IR and sonar sensors are available for indoor use; however, they receive too much interference when operating outdoors. JPL developed a stereo camera and obstacle avoidance algorithm to determine a path to avoid the obstacle. With this “Smart Camera,” small UGVs will have the capability for obstacle avoidance.

Iagnemma [8] discusses UGV terrain identification as a factor to improve high-speed operation. It seeks to identify terrain through the use of visual cues (color, shape), wheel-terrain interaction, and auditory identification. These systems are then used to adjust vehicle speed with relation to expected terrain response.

Anwar [9] utilizes electromagnetic-electro-hydraulic brake-by-wire system to control the yaw rate on a simplified linear model. A yaw moment is the rotation about the vehicle’s vertical axis. The equation for the vehicle’s measured yaw rate stems from its yaw inertia, longitudinal and lateral forces on the tires contact patches, and angle of the front tires. Assumptions and substitutions of cornering coefficients and slip angles, and road friction coefficients reduce the yaw rate equation. Anwar then utilizes a matrix equation of the body slip angle and the yaw rate to determine the vehicle dynamics. For the desired yaw rate, Anwar formulates his “predictive control law.” This yaw rate is based on the vehicle’s steering angle and speed. He derives his “generalized predictive control” using Diophantine prediction equation. The controller uses actuators to brake the system based on whether the vehicle experiences understeer (yaw rate is less than desired yaw rate) or oversteer (yaw rate is larger than desired yaw rate). Based on oversteer or understeer, the vehicle brakes one or two brakes on one side of the vehicle based on direction of the turn. The amount of brake torque on the tire determines the controlled yaw rate. Anwar gives an equation for his eddy current machines based on rotational speed.

Edge [10] reports on the Lynchbot project. Army Research Labs at Aberdeen Proving Ground fielded the Lynchbot: an E-Maxx-based vehicle with tele-operated control and vehicle video feedback. ARL engineers found it beneficial to use brushless motors, a different speed controller that has better low-speed performance, and heavy shock absorbers. The Lynchbot uses military batteries for ease of logistics.


3 VEHICLE DESCRIPTION

The USMA UGV uses an off-the-shelf E-Maxx chassis manufactured by Traxxas (www.traxxas.com), Fig. 2 shows the vehicle with electronics. This vehicle is a four-wheel-drive radio controlled model. Parts cost is under US$1500 for the configuration shown.

Specifications are given in Table 1.
The E-Maxx chassis is well suited to be an unmanned vehicle platform. Its speed and mobility are impressive. Suspension design is A-Arm type, identical to common automotive suspension except that the E-Maxx has two springs and two shock absorbers per wheel. Suspension stiffness is adjustable by positioning the shock absorbers in any of various mounting holes and replacing the springs with aftermarket springs of various spring rates. Different viscosities of oil for the shock absorbers are also available.

The model is sold with two 550 size brush dc motors, both motor pinion gears engage the flywheel. Arranged in this way the motors are mechanically in series. The vehicle comes with an electronic speed controller that controls electric current to the motors.

Lithium-Polymer (LiPo) batteries are used for their high energy density to maximize UGV mission time between charges. Run time with the LiPo battery pair is about one hour, but it depends strongly on driving habits and terrain. The battery specifications are listed in Table 2.

<table>
<thead>
<tr>
<th>Table 1: E-Maxx Vehicle Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top speed</td>
</tr>
<tr>
<td>Vehicle Weight</td>
</tr>
<tr>
<td>Suspension</td>
</tr>
<tr>
<td>Steering</td>
</tr>
</tbody>
</table>

The USMA UGV team is also experimenting with brushless motors. The brushless motors are more efficient than brushed DC motors, they are closed motors whereas the brushed DC motors are open to dirt and water, electrical noise is less than that of brushed motors due to brush arcing, and lighter weight since one brushless motor replaces two brushed motors.

4 Wheel Load Sensing

Expert rally drivers are cognizant of wheel-to-wheel load transfer [13] because it directly impacts the driver’s ability to control a car during a skid or to induce skidding when desired. Intentional skidding is known as drifting. Decelerating by means of braking or reducing pressure on gas pedal will cause load to shift from the rear wheels to the front. Load shifting, both front-to-back and side-to-side is done intentionally by rally drivers to facilitate controlled drifting, i.e. sideslip, such that the car’s velocity vector is not aligned with the heading of the car. Driver steering input, braking input, and accelerator input during a turning maneuver depend on much experience and rapid judgment of the environment and car motion. Developing this level of intelligence in an autonomous vehicle is impossible at this time, but the vision of expert autonomous rally racing is inspiring. It is anticipated that controlled drifting can be achieved by autonomous unmanned vehicles by means of wheel load measurement as a humble first step. This article covers one method for estimating wheel loads; vehicle drifting control algorithms will be the subject of future work.
One means of sensing vertical wheel reaction forces is to measure the deflection of the suspension components. The E-Maxx has conventional automotive suspension with upper and lower control arms, a steering knuckle, and a shock absorber / spring assembly. Fig. 3 shows a front view of the E-Maxx vehicle with one wheel being held in the fully up position by a force gauge. The blue control arms are visible, and the shock absorber with the red spring is also visible in the photograph.

The angle theta of the lower control arm can be measured by a Hall Effect device and permanent magnet. A simplified but usable spring-mass-damper model of the wheel assembly can be obtained by making the following assumptions.

1. The sprung mass, m, is assumed to be concentrated at one point;
2. Rate of change estimates can be derived from measurements of the angle theta. The validity of this assumption requires an appropriately fast sampling rate;
3. Wheel loads in the horizontal plane do not affect the angle theta.

The angle beta is formed between the lower control arm and the shock absorber / spring. The mass is represented by the constant m. Governing equations can be derived from Newton’s second law assuming that the frame is fixed and summing moments about the inboard pin joint of the lower control arm.

The time-varying length of the shock absorber / spring is:

$$L = \sqrt{s^2 + p^2}$$

where:

$$s = b - h \sin \theta$$
$$p = h \cos \theta - a$$

The change in length of the shock / spring is:

$$\Delta L = L - L_0$$

where the length of the shock / spring when \( \theta = 0 \) is:

$$L_0 = \sqrt{b^2 + (h - a)^2}$$

The time-rate-of-change of the shock / spring length is:

$$\dot{L} = -h \dot{\theta} (s \cos \theta + p \sin \theta) / L$$

where \( \dot{\theta} \) is the time rate of change of \( \theta \).

The reaction load exerted by the ground acting up on the wheel is:

$$F = M + mgq \cos \theta + h(F_x + F_y) \sin \beta$$

where the moment of forces about the lower pin is:

$$M = J \dot{\theta}$$

and the mass moment of inertia of the concentrated mass m taken about the lower pin is:

$$J = mq^2$$

and the second time derivative of the angle \( \theta \) is \( \ddot{\theta} \). The angle \( \beta \) is:

$$\beta = \theta + \tan^{-1} \left( \frac{s}{p} \right)$$

The spring force is:

$$F_s = k \Delta L - F_p$$

where \( F_p \) is the absolute value of the compressive preload force in the spring at \( \theta = 0 \). The spring force \( F_s \) is positive if tension, negative if compression. The damping force due to the shock absorber is:

$$F_c = c \dot{L}$$

The damping force \( F_c \) is positive if tension, negative if compression.
Fig. 5: Suspension static stiffness

Fig. 5 shows measured static force values superimposed on the force predicted by equation (7) with $\dot{\theta}$ and $\ddot{\theta}$ set equal to zero. The measured values were obtained from increasing and then decreasing the vertical load on the tire. Hysteresis is present due to friction in the shock absorber. The measurements did not cover the entire range of motion of the suspension, but went up to 0.164 radians. Suspension angle was measured with a Hall Effect sensor mounted on the frame interacting with a permanent magnet on the lower control arm. A linear model relating the angle to the voltage was obtained from the data:

$$\theta = -1.081 * V + 2.3074 \quad (13)$$

Where $V$ is the Hall Effect sensor voltage. This characterization was obtained based on seven data points ranging from -15º to +15º.

5 PROGRESS ON AUTONOMY

Autonomous control of the USMA UGV under a BASIC Stamp microcontroller has been demonstrated at the US Military Academy. The system integrates a Garmin E-Trex GPS unit and a digital magnetic compass to navigate; the microcontroller executes an action when the vehicle arrives at a preset location. Control can be switched between manual and autonomous at will. The current effort is to further develop the algorithm and to transfer it to the a dsPIC microcontroller manufactured by Microchip. The dsPIC is a 16 bit microcontroller that can process instructions at 40 million instructions per second (MIPS). This processor has a variety and quantity of digital and analog inputs and outputs that make it suitable for small, low-cost unmanned vehicles.

6 CORNERING MANEUVER

Vehicle maneuvers can be documented with an overhead-mounted video camera. Fig. 6 shows a setup where the camera is mounted on the end of a ladder 15 feet above ground. The 90º turn was marked out on the ground directly below the camera; the orange cone visible in Fig. 6 marks the inside of the corner. The video camera is fitted with a wide angle lens to obtain a good field of view.

![Camera](image)

**Fig. 6: Bird’s Eye Camera Setup**

It will be possible to analyze video footage frame-by-frame to measure vehicle velocity, yaw angular velocity, and sideslip of the UGV executing the maneuver.

Timing gates were built to sense vehicle velocity as it enters and exits the course. These gates were implemented using retro-reflective photo sensors to detect the presence of the vehicle as it crosses the imaginary starting and finishing lines. With a pair of these sensors mounted on parallel beams a known distance (1 meter) apart Fig. 7, velocity can be calculated. These gates can also be used to measure the time to complete the maneuver, an excellent measure of performance. A microcontroller from the Atmel AVR family, the ATmega16, was used to measure the gate time. As the vehicle enters the gate, the first sensor generates a high pulse which is connected to an external interrupt pin on the microcontroller. The interrupt service routine resets a 16-bit counter which is incrementing every microsecond. The second sensor also generates a high pulse and is connected to another external interrupt pin. This second interrupt service routine captures the current count and then displays the time in seconds and milliseconds on a terminal window connected to the serial port.
**Fig. 7:** 90° turn lane with entry timing gate and exit timing gate to measure velocity.

### 7 CONCLUSION AND WORK TO FOLLOW

Immediate next steps in this effort are to document maneuvers with the birds-eye video setup, and synchronizing logged data with video. A major effort will be to develop algorithms in Matlab Simulink® and convert to dsPIC-compatible code. It is a primary aim to accomplish a drifting turn autonomously and then seek robustness to variety in the environment and vehicle. A related area if interest is roll-over mitigation. Possible directions of the UGV project in the future are the incorporation of vision capabilities along with more computing power beyond dsPIC, programming of leader-follower and swarming behaviors, and implementation of adaptive behavior that responds to changes in terrain. Another possible research direction is to evaluate individual wheel braking for yaw moment control.

UGV research seeks to improve the reliability and autonomy of robotic platforms and allow for adaptability to different situations and terrain. Improvements in steering control promise greater precision and adherence to a prescribed path. Terrain identification will improve speed and maneuverability of small UGVs and prevent dangerous situations. Localization improvements will allow teams of UGVs to maneuver and remain in formation while performing their tasks. The E-Maxx vehicle with upgrades for ruggedness is a suitable platform for UGV development.

### 8 ACKNOWLEDGEMENTS

The authors express their thanks to the U.S Army Tank and Automotive Research Development and Engineering Center for funding this project.

### REFERENCES

13. T. Hanson, *Vehicle Control Technologies*, personal conversation, August, 2009