Estimating wheel slip for a forest machine using RTK-DGPS

Thomas Hellström[1], Ola Lindroos[2], Ola Ringdahl[1]*, and Iwan Wästerlund[2]

[1] Dept. of Computing Science, Umeå University, SE-901 87 Umeå, Sweden.

[2] Dept. of Forest Resource Management, Swedish University of Agricultural Sciences, SE-901 83 Umeå, Sweden;

* Corresponding author: ringdahl@cs.umu.se (O. Ringdahl)

Authors appear in alphabetical order.

Keywords: Forestry; asphalt; gravel; sand; snow; terrain; forwarder;

Abstract

Wheel slip may increase the risk for wheel rutting and tear up ground vegetation and superficial roots and thereby decreasing the bearing capacity of the ground floor, but also reducing the growth of nearby standing forest trees. With increased slip more energy is consumed for making wheel ruts in the ground, with increased fuel consumption as a result. This paper proposes a novel method for measuring slip in an uneven forest terrain with an 8WD forestry machine. This is done by comparing the wheel velocity reported by the machine and velocity measured with an accurate DGPS system. Field tests with a forestry machine showed that slip could be calculated accurately with the suggested method. The tests showed that there was almost no slip on asphalt or gravel surfaces. In a forest environment, 10-15 % slip was common. A future extension of the method enabling estimation of the slip of each wheel pair in the bogies is also suggested.

1 Introduction

One of the major focuses in Swedish forestry is to decrease fuel consumption at forestry work [13]. Presently it is estimated that the average fuel consumption is 1.7 l/m^3 harvested wood from stump to landing at road side [4]. Usually this figure includes a harvester felling and bucking the trees, and a forwarder for the terrain transport of timber to the landing. However, in the work performed large masses are handled (trees or logs) and, thus, the machines are often heavy. Machine masses are especially high in the work of transporting trees or logs from the terrain to roadside landing points, as it is operational and fuel efficient to maximize payloads with good transport speed. At harvesting operation it is suggested that the forwarder fuel consumption could be decreased by improving the transmission chain. Another motive to look closer at the transmission chain is the concerns about soil damage at harvesting operation. One reason for this is the year around harvesting operation to supply the industry with timber. The expected more rainy periods and less frozen ground in north Europe due to climate change will increase soil moisture content and reduce the bearing capacity which in turn would increase wheel slippage. Good planning before harvesting should steer the operation towards better areas, but unexpected heavy rains can alter ground conditions very fast. Heavy axle loads and wheel slippage will create deep rutting and soil compaction and increase the fuel consumption [19, 25, 26]. Thus, there is generally a conflict between minimized soil disturbance and maximized operational efficiency.

Another reason to look at the transmission chain is to see if wheel slip could be avoided by having better load-adapted wheel propulsion [27, 26]. Slip is defined as how the speed of the traction elements differs from the forward speed of the vehicle [2]. Most forestry machines are made for good mobility in uneven terrain, and the basic principles have been adopted by most machine manufacturers during the years. Now, with increased focus on trafficability, some of the previously accepted design principles can be questioned. Some slip is needed for good traction. On the other hand it is known that slip may increase the risk for wheel rutting in the forest [18]. The slip may tear up ground vegetation and superficial roots and thereby both decreasing the bearing capacity of the ground floor but also reduce the growth of nearby standing forest trees [27]. With increased slip, energy is consumed for making wheel ruts in the ground with increased fuel consumption as a result [5].

It is relatively easy to measure the difference between the wheels' speed on even ground. This is used by many car manufacturers for slip control and traction control. Technical solutions for the same measurements in off-road forestry vehicles have also been suggested [24]. However, the rough off-road terrain makes the estimation of slip more challenging than for regular roads. Small obstacles, such as stumps and stones that have to be run over add extra distance to the travelled distance for each individual wheel, and the comparison to vehicle speed becomes more complex.

The main objective of the work presented in this paper was to develop and evaluate a method measuring average slip in uneven forest terrain with an 8WD forestry machine with hydrostatic-mechanical transmission. Additionally, a method to measure and analyse slip of individual wheels is proposed. In a previous study, the forest machine's own data transmission measurement was used and combined with GPS-data for measuring mobility parameters [24]. We use a similar, but enhanced, technological approach specially adapted for slip measurements.

The paper is divided in two major parts. One part is a literature study of relevant work previously done in the area of wheel slip. The other part describes the developed method and contains a report on field studies carried out on a Valmet 830 forwarder to evaluate the method.

2 Background

To better understand the discussions later in the paper, this section contains a short background to satellite navigation systems and forest machine transmission.

2.1 Satellite navigation systems

Today, two different satellite navigation systems are available; the American GPS (Global Positioning System) and GLONASS (Global Navigation Satellite System) from Russia. These two systems are quite similar, and many GPS receivers are able to use the GLONASS signals as well, to increase the accuracy of the position estimation. The main difference is that GLONASS has fewer operational satellites due to neglected maintenance since the fall of the Soviet Union, but Russia is committed to fully restore the system by 2011. Currently (March 2010) 17 of 24 satellites are operational [11]. An advantage of GLONASS is better coverage at high latitudes (>60° North). A new system, Galileo, is under development in Europe but is not yet in operation. The launch of the first two operational satellites is scheduled for the end of November 2010, followed by the launch of the third and fourth operational satellites in April 2011 [9]. The technology described below is common to all three systems with just minor differences.

Each GPS satellite transmits two carrier waves (denoted L1 and L2) modulated with ranging codes (Pseudo Random Noise, PRN) [6]. A standard GPS receiver measures the time-of-flight for the PRN-signals from 3 to 12 satellites. From the corresponding distances, and information about the exact location of each satellite, the position of the receiver can be estimated. Velocity and heading estimates are also possible to compute, based on the Doppler Effect on the signals from the satellites. The accuracy of the velocity estimates is about 0.1 ms^{-1}. Basic GPS receivers have a position accuracy of around 15 meters 95 % of the time. An extended technology is differential GPS (DGPS) which has around 0.5 meters accuracy [8]. This technique utilizes two receivers; a base station located at a known position, and a moving receiver placed on, for instance, a vehicle. The base station is able to calculate the position error in the GPS-signal it receives, and can send correction data to the mobile receiver [6]. To get an even higher accuracy in the position, Real Time Kinematics DGPS (RTK-DGPS) can be used. This is an extension of DGPS where the two receivers use not only the ranging codes, but also the carrier waves. To calculate the distance to each satellite, the number of full periods of the carrier wave from the satellite to the receiver is required. This is referred to as solving the integer ambiguity, or getting a “fix solution”. In addition to this number, the fraction of the last period, given by the phase of the wave, has to be calculated [28]. A non-stationary RTK DGPS is capable of delivering positions with errors between 2-20 cm and headings with errors of less than 0.1 degree [17, 21]. However, regardless of the GPS type, the technology has limitations that make a GPS system insufficient as the only position sensor for a forest machine. The most common problems involve obstruction of line-of-sight to satellites, multi-path problems and active jamming from other radio sources [8]. Therefore, a GPS system is often combined with *Inertial Navigation System* (INS) or odometry.

2.2 Forest machine transmission

One of the most commonly used machines in forestry is the forwarder (Figure 1). A forwarder is used in the Cut-to-length method to carry the cut timber from the forest to the roadside landing (for an overview of machine evolution see [7]). The carrying capacity is normally between 8 and 18 tonnes and commonly in Nordic forestry the machines have 8 driven wheels (8WD), for improved comfort and mobility on soft ground. The machines have an articulated steering and to further improve mobility in rough terrain front and rear part has a connection that can pivot somewhat which enable the parts to move sideways rather independently of each other. During work, a forwarder normally drives at rather low speed in forest terrain; usually less than 1.3 ms^{-1} when driving unloaded and ca. 0.8 ms^{-1} when driving loaded [16].

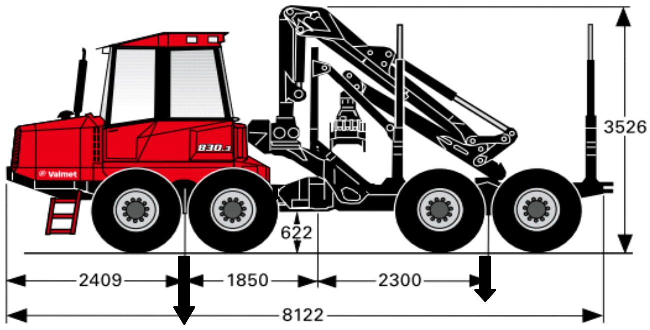


Figure 1. Example of a typical forwarder, a machine that carries cut timber from the forest to a landing. The example show the forwarder type used in the field studies. Measurements in mm and the large arrows indicate relative axle load of the unloaded vehicle. Drawing courtesy of Komatsu Forest AB.

The transmission in a modern forwarder is commonly hydrostatic–mechanical, which means that the diesel engine is working a hydraulic pump that propels a hydraulic motor. One or both of pump and motor could be adjustable to give the machine a desired and constant speed. The hydraulic motor is connected to a drop-box. With two gears and a determined gear ratio there is a mechanical connection via drive shafts to the front and rear axle. Each axle has a differential which is open during normal operation but can be locked from the cabin during off-road operation at difficult passages. The machine has a fixed gear ratio between front and rear axle. The front is often given a somewhat higher speed than the rear axle to avoid pushing of the rear axle when taking curves which might jeopardise stability [14]. The articulated steering on forwarders is often positioned in front of the middle of the vehicle to further increase the stability at curve driving. This also decreases rutting and makes room for long timber with the load centred over the rear axle. On the other hand this means that the wheels in the front and rear parts respectively travel different distances in curves and, as a result of the fixed gear ratio, a forced slip is induced. To enable 8WD each axle is equipped with a powered bogie. From the differential, the torque is usually transmitted with gears in the bogie to the wheel axles such that the two wheels in each bogie are given the same rotational speed. The single pivot point for the two wheels gives the advantage that the inclination of the axle will be considerably reduced when driving over objects such as stones (as illustrated in Figure 2), compared with an axle with a single wheel. The net traction is at least equal to, or in most cases higher than those for both single and dual wheel systems [3]. The bogie will also give the machine increased side stability.

Figure 2. Bogie negotiating a stone and reducing the obstacle height. Photo courtesy of Komatsu Forest AB.

The drawbacks with a bogie are the power needed to pull the wheels around in a curve (side skidding) and the lifting behaviour of the bogie at high traction due to the turning moment from the axle. Thus, at high traction the front wheel is lifted and the rear one pressed down. This leads to different wheel radii and thus forced slip. The phenomenon is illustrated in Figure 3, in which a 2 cm difference in rolling radius results in the front wheel trying to cover a 0.12 m longer distance than the rear wheel for each revolution [14]. This corresponds to ca. 2.5 % slip.

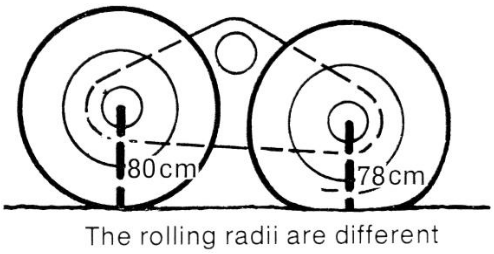


Figure 3. Bogie lifting at high torques causes the front wheel to slip since the rear wheel diameter decreases (from [14]).

In order to have a good carrying capacity (low ground pressure), it is common to use wide tyres (700 mm or wider). Most of them are hitherto made by hand and are almost impossible to make identical. According to The Scandinavian Tire & Rim Organization (STRO), the diameter variability at manufacturing is ±1.5 %, which results in 3 % slip if two wheels with max and min diameter respectively are mounted on the same bogie. The same kind of forced slip is caused by differences in tyre inflation pressure. The inflation pressure is set at delivery from the factory and is normally never checked again until the tyre is replaced.

One major drawback with the present design of forwarders is that the machines are front heavy (approximately 60 % load on the front) when empty (see Figure 1) and the reverse mass distribution when returning to landing. To improve flotation and traction on soft ground, it is common to mount bogie tracks on the rear bogies. This supports the load of timber when going back to the road-side landing but will increase the rolling radii difference between front and rear when driving with empty machine. Thus, commonly tracks are used both on front and rear bogies.

The construction/design of a forwarder is thus a compromise between several contradictory properties. One of the most demanding properties is robustness; the vehicle must withstand the forces from the load when climbing over stones and stumps, up and down hills, and on swampy ground with an expected life time over 20 000 machine hours.

3 Related work

Olsen and Wästerlund [18] reported studies on an experimental forwarder supplied with torque-measuring axles to study the rolling resistance and torque distribution for an 8WD forestry machine. After a short and slow travel straight forward with locked differentials, the front wheels started to slip and the rear wheels were pushing the machine forward (Figure 4). The main reason was that the front part carried 60 % of the load but the inflation pressure was equal on all tyres (200 kPa). Thus the rolling radius was smaller on the front wheels. Furthermore it was found that within the bogies small variations in rolling radii of the tyres plus small variation in inflation pressures were enough to cause torque variations up to 1 kNm. On average 1.5 kNm was needed to propel the 10.5 ton forwarder on gravel ground and 3 kNm on a medium soft grass lane [18].

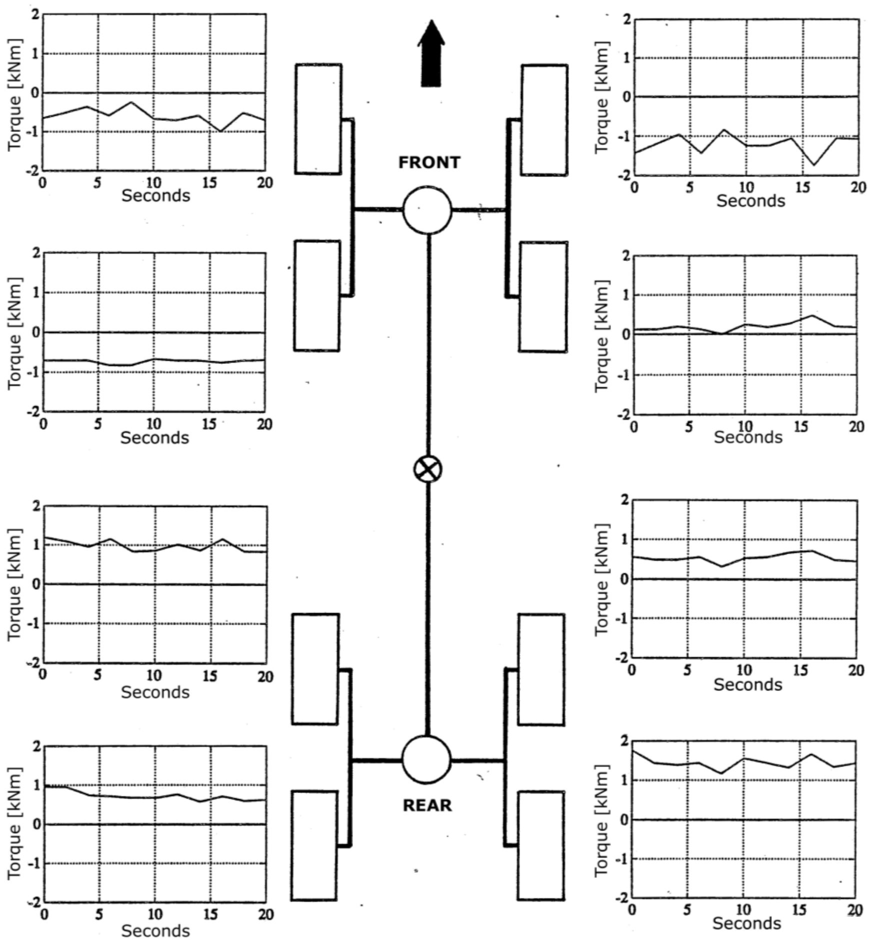


Figure 4. Torque measurements (kNm) on each drive shaft to the wheels when driving straight ahead during 20 seconds on gravel ground with locked differentials (Figure derived from [18]).

Driving over a 16 cm high beam resulted in a partial difference in road length of 8.5 % and increased the needed torque 1.7 times. A similar thing happened when curve driving on level gravel ground proving that bogies are heavy to pull in a curve but also showing the restraints from wheels pushed to different distances.

Shoop et al. [23] measured traction and slip on a 4WD jeep when driving in soft terrain and snow. Wheel slip was measured by using a free rolling axle or a single 5th test wheel on the SAAB friction testing car. A "fifth wheel" as a sulky was successfully used by Mohr & Eriksson [15] when studying an 8WD forwarder driving on level ground. When driving uphill in forest and in curves this measuring technique did not work well, and further slip studies were discarded. Saarilahti and Ala-Ilomäki [22] estimated wheel slip by filming a forwarder with marks on the rims, and reached values between 10 and 20 % with increasing values in slopes.

Angelova et al. [1] suggested a framework for learning to predict slip for a Mars rover. The terrain in front of the vehicle was analysed using stereo camera images. Visual features for terrain geometry were used to learn a nonlinear model of the corresponding wheel slip. The correct wheel slip value was measured by the vehicle's sensors when the viewed and analyzed location was later traversed. In this way, the vehicle could learn to predict future slip values, something which can be used to avoid hazardous or slippery areas.

Another way of estimating slip is by using a dynamic model of all forces affecting the vehicle [12, 20]. This of course requires that these forces are known, which is difficult to know in the reality.

4 Definitions

The periphery of an idealised rolling wheel with radius *r* moves at a speed in a direction perpendicular to the wheel axle rotating at angular velocity ω. In reality, both magnitude and direction may differ from this idealised situation. The actual vehicle velocity is denoted by *V*. The *longitudinal* slip of a wheel is the difference between the wheel velocity v_w and *V*. By normalising the difference we arrive at the following definition of slip coefficient *S* [10]:

$$S = \frac{v_w - V}{v_w} = 1 - \frac{V}{v_w}. \quad (1)$$

V may for example be computed from consecutive estimated positions from a DGPS, as is done in this paper.

5 Development of a slip measurement methodology

5.1 Machinery and terrain conditions

The test machine was a Valmet 830 with a 100 kW engine, as shown in Figure 1. All eight tyres were Nokian ELS with the dimension 700/40-22.5 with inflation pressure 200 kPa. The gear ratio was 21.95:1 for both front and rear axle. The vehicle was driven unloaded during all experiments, such that 63 % of the in total 10 tons were on the front axle. The forwarder was equipped with tracks on all bogies during the forest run, but was without tracks during the other runs.

For this study, experiments on four different ground types were performed: asphalt, hard gravel, sand, and forest terrain. On level areas of dry asphalt and hard gravel, the forwarder was accelerated from standstill to a set constant speed while being driven straight ahead with 8WD turned on. To test the method's ability to detect large slip values, a test run was also conducted on a level area with loose sand. To increase the possibility of slip, the 8WD was turned off and the differentials were not locked. To evaluate the method in a real forest environment, a test was also performed in a snow covered (ca. 0.5 m deep) clear-cutting area with stones and stumps and a gentle slope (< 5° inclination). The 260 meter long path was laid out with many turns making the vehicle go in most directions along the slope.

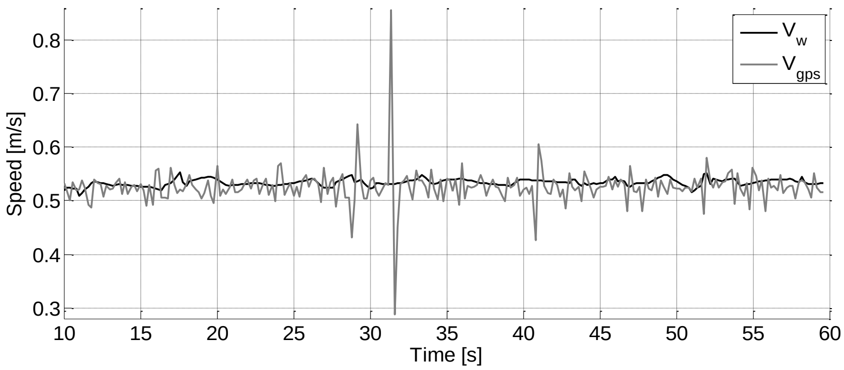
5.2 Speed measuring technique and signal filtering

The speed of the machine was measured via its standard odometer, which used a magnet and pulse encoder on the outgoing shaft of the transmission hydraulic motor. The manufacturer calibrates the odometers by driving the machines known distances while counting pulses. The signals are converted via the transmission computer to provide speed and travelled distance for the cabin display (i.e. the odometer). Hence, the wheel speed v_w can be regarded as an average speed for all eight wheels. The vehicle velocity V was estimated from consecutive position data from a real-time kinematics differential GPS (RTK-DGPS), and is henceforth denoted v_{gps}. Raw data from the GPS was compensated for the mounting pose of the GPS antenna (on the vehicle's roof), and the vehicle's current heading, roll, and pitch such that the resulting value v_{gps} is the speed for a point located in the centre of the front part of the vehicle at ground level. For calculation of individual wheel slip, the corresponding transformation would have to be done for each wheel. The timestamps for the sensor readings differed between the two sensors, so the values for v_{gps} and v_w were linearly interpolated to have matching timestamps.

Figure 5 (top) shows speed from the GPS and wheel speed when driving on asphalt. At low speed, the sensor readings are too noisy to be used to calculate slip. The noise was reduced by applying a symmetric moving average filter to each speed reading $v(k)$ (for both v_{gps} and v_w):

$$v(k) = \frac{\sum_{i=-n}^{n} v(k+i)}{2n+1} . \qquad (2)$$

The constant n was set to 10 such that the standard deviation of the resulting slip on asphalt was about 0.5 %, which was decided to be an acceptable accuracy. The results of filtering v_{gps} and v_w from the track *Asphalt 1* (see Table 2) can be seen in Figure 5 (bottom).



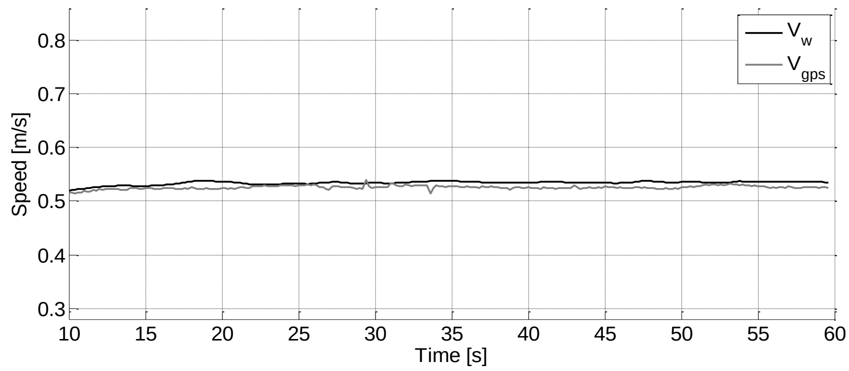


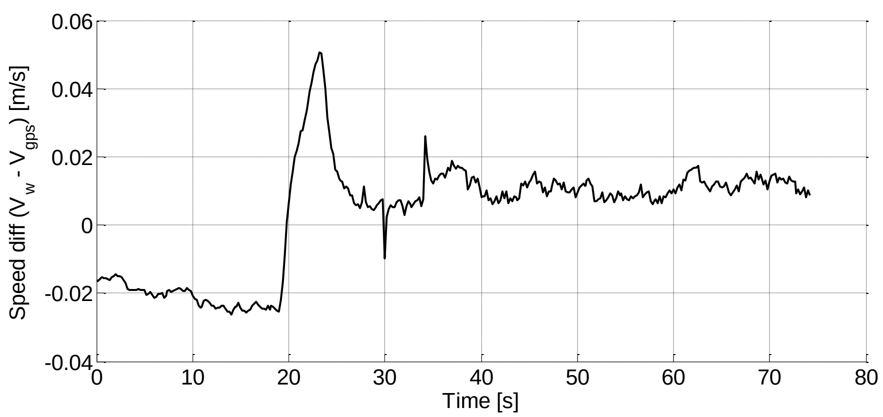
Figure 5. Readings from the wheel speed sensor and the GPS (v_w and v_{gps}) are too noisy to be used directly as seen in the upper figure. After applying a moving average filter (Equation 2) the readings are much smoother, as seen in the lower figure. The data shown is from the track *Asphalt 1* (see Table 2).

5.3 Calibration and data delimitation

When driving at constant speed on asphalt, there was a slight difference between the GPS speed (v_{gps}) and the wheel speed (v_w), as can be seen in Figure 6 (top). To check if this difference was statistically significant a two-sample t-test was performed. The null hypothesis was that v_{gps} and v_w are independent random samples from normal distributions with equal means and equal but unknown variances, against the alternative that the means are not equal. For asphalt the null hypothesis could be rejected at the 5 % significance level on all three tracks, see Table 1. The difference is mainly caused by the wheel speed sensor not being correctly calibrated for the given conditions (e.g. different tyre inflation pressure or vehicle mass compared to the manufacturer's calibration), but also originates from the vehicle transmission forcing wheel slip, as described in Section 2.2. Since we are only interested in slip caused by varying ground conditions, we define the slip level on asphalt to be zero by introducing a calibration constant *c* in Equation 1 according to:

$$S = 1 - \frac{v_{gps} - c}{v_w} \tag{3}$$

The average of the mean values μ in Table 1 was used to determine the calibration constant *c.* Based on observations from the asphalt driving, *c* was estimated to 0.009 ms^{-1} for asphalt, gravel and sand. Since the tests in real forest environment took place at a later occasion and with tracks mounted on all bogies, a new calibration value (*c*=0.02 ms^{-1}) was established by running straight ahead along a nearby forest road.



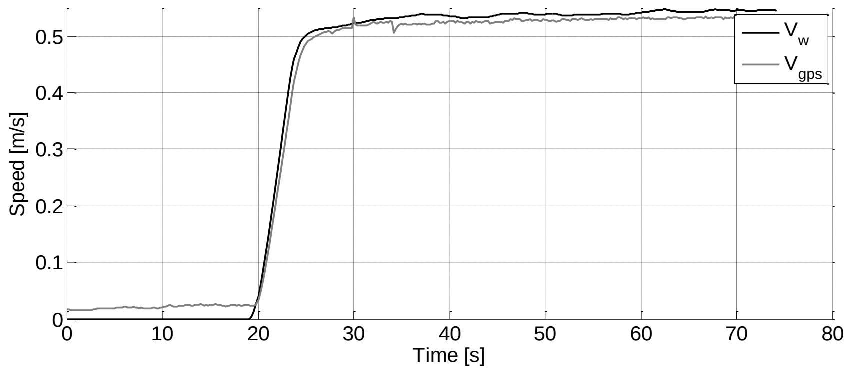


Figure 6. Difference between wheel and GPS speed (v_w and v_{gps} respectively) (upper pane) and the actual values for v_w and v_{gps} (lower pane) when driving the track *Asphalt 2*.

Table 1. Two-sample t-test for the hypothesis that v_w and v_{gps} have equal mean. µ is the mean value, σ the standard deviation, CI the 95% confidence interval, and *df* is the degrees of freedom

Track	µ	ó	CI	df	t-value	P
Asphalt 1	0.0083	0.0036	0.0079 - 0.0087	247	-3.11	<0.001
Asphalt 2	0.0108	0.0140	0.0104 - 0.0113	220	8.11	<0.001
Asphalt 3	0.0091	0.0048	0.0084 - 0.0097	202	0.20	<0.001

5. 4 Possible error sources

As can be seen in Figure 6, the estimated speed difference is sometimes negative when standing still (the first 19 seconds). The reason for this is noise in the GPS-position in the order of a few millimetres, as shown in Figure 7. This may cause negative estimated slip values when standing still (or driving very slowly). Since the estimated slip values approach negative infinity when speed reaches zero, data for very low speed is not used in the slip calculations.

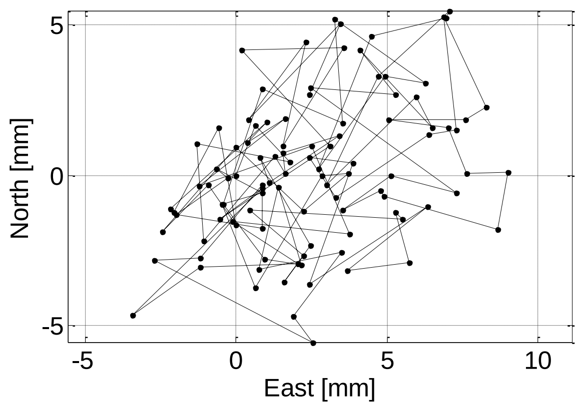


Figure 7. Position data delivered by the RTK-DGPS system for a non-moving receiver. The noise (standard deviation 1.98 mm in the shown example) leads to a non-zero speed estimate based on consecutive positions.

When the vehicle was accelerating on asphalt, the calculated slip values were very high. The high slip could not be confirmed by direct observation of the wheels, and instead the obtained slip was most likely caused by delays in sensor readings. For these reasons, slip values where calculated on the part with constant speed. The effect of errors due to delays in sensor readings is further discussed in Section 6.

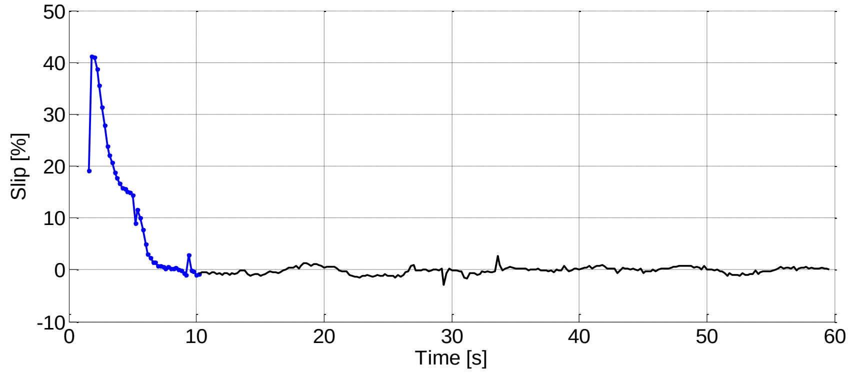


Figure 8. Estimation of slip when driving on level asphalt (track Asphalt 1, the same as in Figure 5). The acceleration phase is marked with a dotted line. The slip value presented in Table 2 is based on the part with constant speed (from 10 s and onwards).

5.5 Observed slip

Estimated slip values for the tracks with constant ground conditions (three on gravel and three on asphalt) are presented in Table 2. The vehicle was driven along straight lines and the slip was assumed to be constant during the entire run. The mean values for the asphalt tracks are very close to zero, since they were used for calibration as described above. The values for the gravel tracks are somewhat larger but all values are well within the random variations, quantified by the standard deviation σ.

Table 2. Mean (μ) and standard deviation (σ) for slip values [%] when driving straight forward at constant speed on asphalt and gravel. N is the number of observations.

Track	μ	ó	N
Asphalt 1	-0.1	0.7	248
Asphalt 2	0.3	0.6	221
Asphalt 3	-0.1	0.9	203
Gravel 1	0.3	0.7	327
Gravel 2	0.3	0.9	122
Gravel 3	0.8	0.7	78

On the loose sand track, the vehicle was driven straight ahead until it almost stood still due to large amounts of wheel slip. Figure 9 shows that the GPS detects how the vehicle slows down after about 13 seconds, ending up with a vehicle speed close to zero. The wheel speed decreases only slightly during this time, and the slip increases from about 5 % to almost 85 %.

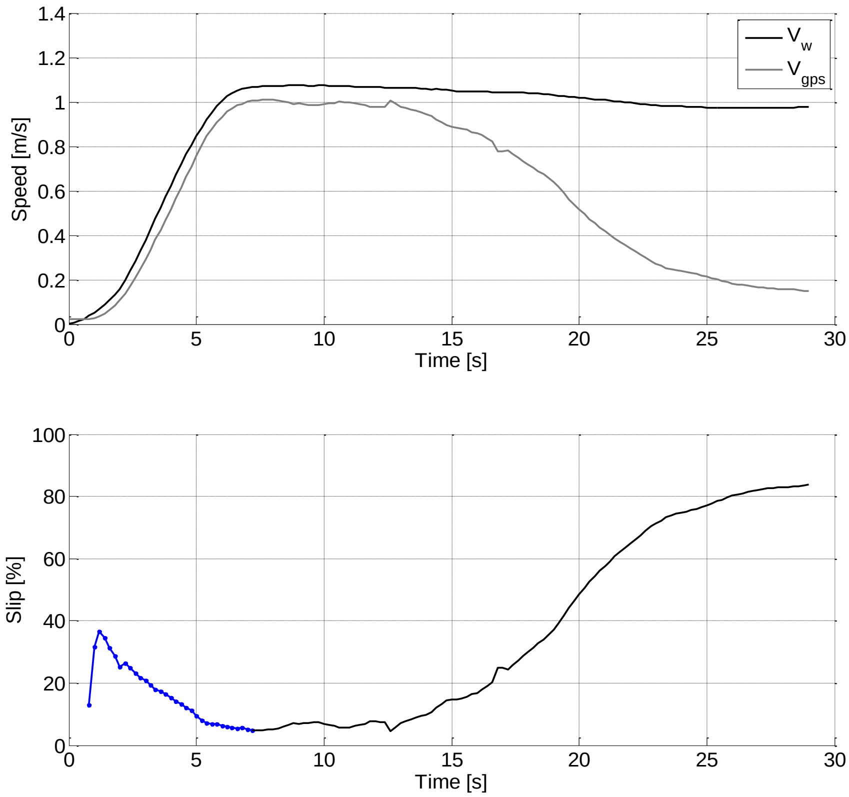


Figure 9. Estimation of wheel and GPS speed (v_w and v_{gps} respectively) (upper pane) and slip (lower pane) when driving with a set constant speed on level terrain with loose sand.

The slip values recorded in the forest environment were higher than on asphalt and gravel (Figure 10). Moreover, slip values varied considerably over time, as expected considering the roughness of the terrain. The estimated slip value reached up to 10-15 % and was at some occasions negative (-5 %). The computed negative slip values can be both caused of real sliding of the machine but may also be within the accuracy in the measurement of slip as estimated during the calibration run (σ =2 %). These variations were probably due to the mounted bogie tracks. As already described in Section 2.2, differences in construction and tyre inflation pressure are other possible sources for these variations.

In general, the estimated random variations indicate limits for the expected accuracy and stability of the measuring method.

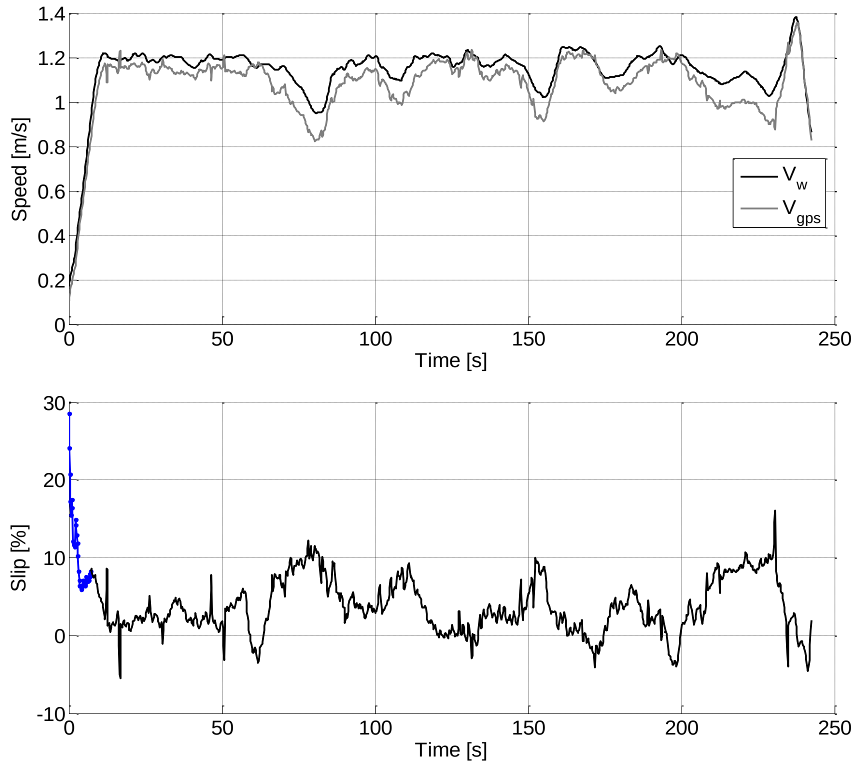


Figure 10. Estimation of wheel and GPS speed (v_w and v_{gps} respectively) (upper pane) and slip (lower pane) when driving with a set constant speed in forest terrain.

6 Discussion and conclusions

The field study verifies that the slip of an 8WD machine can be estimated by comparing the GPS-based speed with the wheel speed, both on even and rough terrain. The method can be a useful tool for the improvement of the transmission chain of a 6WD and 8WD machine, decreased fuel consumption and improved trafficability of all kind of off-road vehicles. However, in the present setup, the computation of accurate slip values requires both post-processing and delimitation of data.

The sensor readings from wheel odometry and GPS were too noisy to be used directly. To be able to calculate slip, a moving average filter (Equation 2) was applied to correct each speed reading from the two sensors. A drawback with this method is that momentary slip values are hard to estimate, since they are based on filtered speed readings over a time of about 4 seconds. Moreover, the symmetrical filter is not possible to use in real-time since future values are obviously not available. However, the method works well for slip estimation with recorded data.

Slip was not computed during the acceleration phase, since the sensitivity for timing errors in v_{gps} and v_w is particularly high during this phase (see Section 5.4 and Figure 8). The timing errors may be caused by delays in computers and networks used for sampling of v_w. The effect of such timing errors can be estimated as follows. Given a vehicle speed v_{gps}, a wheel speed v_w, and an acceleration a, the difference between computed slip with and without time delay t_d is computed as

$$1 - \frac{v_{gps} - c}{v_w} - \left(1 - \frac{v_{gps} + a\,t_d - c}{v_w}\right) = \frac{a\,t_d}{v_w}. \quad (4)$$

From Figure 6 (bottom), a is estimated to 0.05 ms^{-2} and v_w to 0.5 ms^{-1}. For t_d = 0.1 s, this yields a difference in slip estimate of 1 %. For t_d =1 s the difference in slip estimate is 10 %. In Figure 8, the slip is estimated to be about 5 % the moment before the vehicle reaches constant speed. This could be caused by a time delay of 0.5 seconds but may also be caused by real wheel slip.

Another factor that could cause high estimated wheel slip during the acceleration phase (see Figure 8) is a slow response in the v_w signal. This may be caused by both software filtering of the speed signal from the hydrostat motor and by mechanical play in the transmission chain when accelerating the heavy vehicle from standstill.

In general, computation of slip at low speed is numerically sensitive to errors in both v_{gps} and v_w. This is illustrated in Figure 11 which shows how the calculated slip analytically (by applying Equation 1) depends on ΔV at varying wheel speeds when the true slip is zero. ΔV is the measured difference between v_{gps} and v_w. In the conducted experiments ΔV as high as 0.07 ms^{-1} was observed while accelerating from standstill (Figure 10, top), an error value that at very low speed results in very large errors in estimated slip. However, even though a forwarder normally operates at low speeds (< 1.3 ms^{-1} [16]) ΔV was considerably lower when driving at constant speed (less than 0.02 ms^{-1} on asphalt).

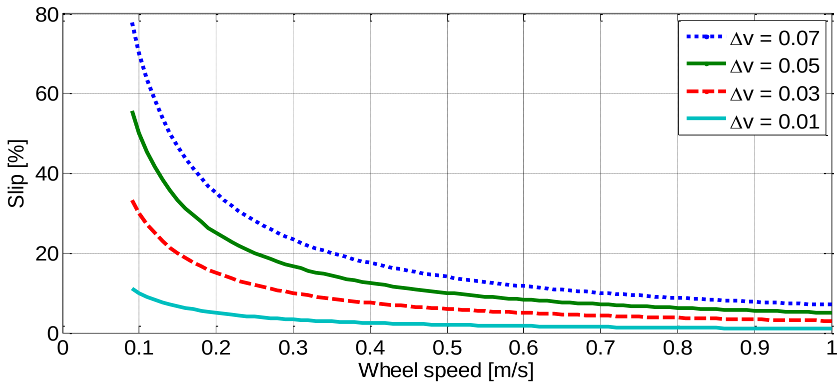


Figure 11. Theoretically calculated slip when the actual slip is zero. The non-zero slip values are caused by errors ΔV (ms^{-1}) in the velocity readings.

On asphalt and hard gravel surfaces the observed wheel slip was very low, with no significant difference in slip between the two ground types. On loose sand a considerable slip was observed, as expected, which verifies that the proposed measuring method is able to detect and estimate slip. The tests in forest environment indicate considerably higher slip values than on gravel or asphalt. As expected, the value varies a lot over time depending on the ground structure.

7 Suggestions for future research and development

The proposed method of using GPS-measured speed and wheel speed to compute slip can be used to detect excessive slip of the whole machine, and automatically activate differential locks to restore the all wheel drive operation. Combined with a more advanced transmission control it would be possible to adapt transmission forces to the current loading of the machine (e.g. empty versus loaded with 10-18 tonnes load of timber in the rear part), and thereby reducing both fuel consumption and slip damage on the ground [27]. However, as indicated in the study, slip estimation at very low speed and during acceleration is problematic. Integration of hard- and software would be able to reduce some of these problems.

Ideally, a transmission control system for 6WD and 8WD working machinery should make all wheels work together with a minimum of slip, in varying types of terrain. Using mean speed from the transmission in the calculation of slip is not sufficient for this kind of application, especially for machines where the rear part is not tracing the front part in curves (e.g. forwarders). A possible technique for estimation of individual wheel slip is presented in Figure 12.

Since the wheels in a forestry machine are connected in pairs to the bogie with a fixed gear ratio, the speed of each wheel pair can be measured by an inductive sensor mounted on the drive shaft to each bogie. By sensing the cogs of an internal cog wheel, high resolution values can be achieved. Figure 12 shows a possible setup with inductive sensors and a pulse counter to measure the speed of each wheel pair. Together with an RTK-DGPS, slip for each wheel pair could be calculated. However, the use of GPS implies that the position and speed for a specific three-dimensional point of the vehicle is recorded. Thus, it is important that this point coincide with the point of interest for the given study [24]. Given the limited contribution in speed variation due to the vertical bogie movements, the GPS-solution in this study makes it possible to estimate speed of all four wheels on the front part of the forwarder. A difficulty may, however, arise when estimating the speed of the wheels on the rear part of the vehicle. Due to inaccuracy in the measured steering angle, the heading of the rear part is hard to estimate correctly. The pitch and roll of the rear part is also difficult to estimate, due to the articulated link. This makes it hard to accurately calculate the position of each wheel, and hence the speed, with the GPS-solution used in this study. One way to overcome these difficulties would be to mount a gyro on the rear part of the vehicle to measure roll and pitch. In this way the speed of the rear part could be derived from the speed of the front part. An alternative way would be to add a second GPS system to the rear part to measure the speed directly.

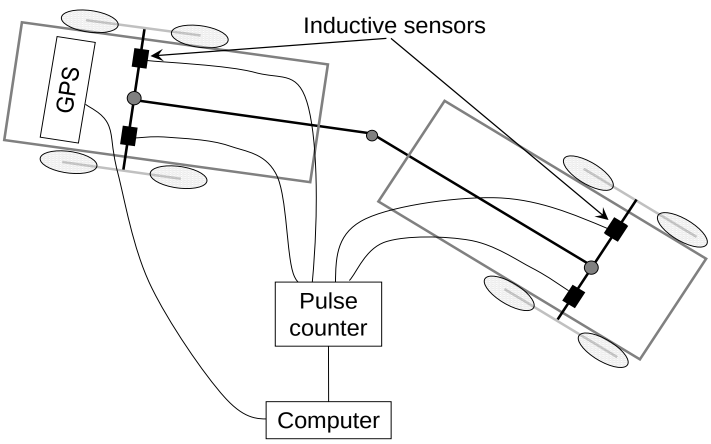


Figure 12. Suggestion for slip-detecting setup for individual wheel pairs. Inductive sensors are connected to a pulse counter to measure wheel speed, which by use of a computer is compared with the wheel pairs' actual speed measured by a GPS.

Acknowledgement

Thanks to Komatsu Forest AB for providing a forest machine for the field studies.

References

[1] A. Angelova, L. Matthies, D. Helmick, G. Sibley, and P. Perona. Learning to predict slip for ground robots. In *IEEE International Conference on Robotics and Automation (ICRA)*, 2006.

[2] Anon. International society for terrain-vehicle systems standards. *Journal of Terramechanics*, 14(3):153–182, 1977.

[3] A.C. Bailey and E.C. Burt. Performance of tandem, dual and single tires. *Transactions ASAE*, 24(5):1103–1107, 1981.

[4] T. Brunberg. Fuel consumption in harvesters and forwarders 2006. Skogforsk, Uppsala. *Skogforsk Result No. 22*, 2006. (In Swedish with English summary).

[5] G. Bygdén, L. Eliasson, and I. Wästerlund. Rut depth, soil compaction and rolling resistance when using bogie tracks. *J. Terramechanics*, 40(3):179–190, 2003.

[6] Chris Drane and Chris Rizos. *Positioning Systems in Intelligent Transportation Systems*. Artech House Publishers, 1998.

[7] K. Drushka and H. Konttinen. *Tracks in the Forest: The Evolution of Logging Equipment*. Harbour Pub Co, Helsinki, Finland, 1997. ISBN 952-90-8616-4.

[8] H Durrant-Whyte. A critical review of the state-of-the-art in autonomous land vehicle systems and technology. Technical report, Sandia National Laboratories Albuquerque, 2001.

[9] European Comission - Mobility & Transport. Galileo, March 9 2010. http://ec.europa.eu/transport/galileo/programme_en.htm.

[10] Karl Iagnemma, Hassan Shibly, Adam Rzepniewski, and Steven Dubowsky. Planning and control algorithms for enhanced rough-terrain rover mobility. In *Proceeding of the 6th International Symposium on Artificial Intelligence and Robotics & Automation in Space: i-SAIRAS 2001*, 2001.

[11] Information-analytical centre, Russian Space Agency. GLONASS constellation status, March 9 2010. http://www.glonass-ianc.rsa.ru/pls/htmldb/f?p=202:20:1682745749350672O876::NO.

[12] Randolph A. Jones, George B. McKinley, Paul W. Richmond, Daniel C. Creighton, Richard B. Ahlvin, and Patric Nunez. A vehicle terrain interface. In *Proceedings of the Joint North America, Asia-Pacific ISTVS Conference and Annual Meeting of Japanese Society for Terramechanics*, 2007.

[13] C. Löfroth and L. Rådström. Fuel consumption continues to fall. Skogforsk, Uppsala. *Skogforsk Result No. 3*, 2006. (In Swedish with English summary).

[14] C-E. Malmberg. *The joint textbook committee of the paper industry*, volume 1, chapter The off.road vehicle, pages 150–158. CPPA, TAPPI, Montreal, Canada, 1989. ISBN 0-919893-75-0.

[15] E. Mohr and U. Eriksson. Traction Forces and Torque Distribution on an 8WD Forwarder. In *11th International Conference of the ISTVS. Lake Tahoe, Nevada, USA*, volume II, pages 803–812, 1993.

[16] T. Nordfjell, D. Athanassiadis, and B. Talbot. Fuel consumption in forwarders. *International Journal of Forest Engineering*, 14(2):11–20, 2003.

[17] M. O'Connor, T. Bell, G. Elkaim, and B. Parkinson. Automatic steering of farm vehicles using GPS. In *Proceedings of the 3rd International Conference on Precision Agriculture*, June 1996.

[18] H-J. Olsen and I. Wästerlund. Terrain and vehicle research with reference to forestry at the Swedish University of Agricultural Sciences. Technical Report 149, SLU, Dept of Operational Efficiency, Garpenberg, 1989. (In Swedish with English summary).

[19] G.S.V. Raghavan, E. McKyes, and M. Chassé. Effect of wheel slip on soil compaction. *J. Agr. Eng. Res.*, 22:79–83, 1977.

[20] Laura Ray, Devin Brande, and James H. Lever. Estimation of net traction for differential-steered wheeled robots. In *Proceedings of the Joint North America, Asia-Pacific ISTVS Conference and Annual Meeting of Japanese Society for Terramechanics*, 2007.
[21] J. F. Reid. Precision guidance of agricultural vehicles. In *SME Meeting, Sapporo, Japan*, 1998.
[22] M. Saarilahti and J. Ala-Ilomäki. Measurement and modelling of wheel slip in forwarding on moraine forest floor. *Scandinavian Journal of Forest Research*, 12(3):316–319, 1997.
[23] S. Shoop, B. Young, R. Algers, and J. Davis. Winter traction testing using three different instrumented vehicles. In *11th International Conference of the ISTVS. Lake Tahoe, Nevada, USA*, volume 1, pages 169–180, September 27-30 1993.
[24] A. Suvinen and M. Saarilahti. Measuring the mobility parameters of forwarders using GPS and CAN bus techniques. *J. Terramechanics*, 43(2):237–252, 2006.
[25] J. Vossbrink and R. Horn. Modern forestry vehicles and their impact on soil physical properties. *Eur.J.Forest Res.*, 123(4):259–267, 2004.
[26] I. Wästerlund. Strength components in the forest floor restricting maximum tolerable machine forces. *J. Terramechanics*, 26(2):177–182, 1989.
[27] Iwan Wästerlund. Soil strength in forestry measured with a new kind of test rig. In *Proceedings of the 10th International Conference of the ISTVS, Kobe, Japan*, pages 73–82, 1990.
[28] Ylin Zhao. *Vehicle Location and Navigation Systems*. Artech House Publishers, USA, 1997. ISBN: 978-0890068618.