Adaptive Tractor Overturn Prediction System (ATOPS)

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Introduction/background

Agriculture in the United States is one of the most hazardous industries, only surpassed by mining and construction. Tractor related injuries account for approximately 32% of the fatalities and 6% of the non-fatal injuries in agriculture. Over 50% is attributed to tractor overturns (Donham, 1999). These deaths are mostly found among older operators (65+) using the 50% of tractors to date without ROPS. Since farms due to the limited number of employees, do not need to comply with OSHA regulations, ROPS are optional and since the threat of dying is not imminent, tractor users tend to ignore it (Cole, 2002).

NIOSH, CDC and other safety related organizations have tried to promote the use of ROPS through incentives, at cost retrofits for tractors built before 1973, formal tractor operator training, and the development of ROPS for special work situations like orchards. Foldable ROPS as well as an automatically deployable ROPS system are available (Powers, et al., 2000). In spite of all these efforts, the number of roll over related fatalities has remained stable, at around 120 per year.

Although ROPS may be an effective means of preventing deaths, operators being flung from the tractor, especially since the use of seat belts is sporadic, may inflict major injuries. Also, an overturn will cause significant damage to the tractor and the ROPS itself (which might or might not be replaced after the accident).

One of the problems with overturns is that the operator does not have a clear indication under which conditions it is about to happen. In other words, there is no direct method that tells the operator how close s(he) got to overturning. Simple tilt sensors can be used to indicate a gradual overturn potential as on a hillside slope. This method is very crude and it needs to be calibrated under a given tractor geometry (which is a dangerous endeavor in itself). When the geometry changes (for instance when a bucket with a load is raised), the center of gravity rises and the tractor will overturn at a much smaller lateral angle.

Another example is the high draft force backward overturn. This overturn happens when the tractor is pulling a very high load at the drawbar, under high traction circumstances or the infamous attempts to remove tree stumps with a high rope attach point to the tractor. The operator has no feel whatsoever when the overturn will occur until it is too late. For this reason it is proposed to develop a sensor based system that 1) indicates to the user that an overturn is imminent before it happens and 2) actively intervenes when it happens.

Determination of an imminent rollover can be done in several ways.

- Tilt sensors can be fitted which determine the angle of the machine in lateral and longitudinal direction with respect to a vertical datum. The tilt indicator can be used as a warning instrument for gradual lateral and backward overturns on a hill slope. It cannot be used to warn the operator for sudden backward overturns (high drawbar pull, or frozen rear wheels) and sudden lateral overturns (high speed cornering). The operator in general does not have time to react to the warning.

- Acceleration sensors such as gyroscopes can be used to determine the acceleration of the machine in all directions to predict the potential for rollovers in the dynamic situation such as a fast turn scenario or a sudden backward overturn. As in the case of the tilt sensor, the gyroscope only detects the occurrence of an overturn and cannot serve as a hazard proximity instrument. The operator simply does not have time to react to it. A modern development is the solid-state gyroscope, which is very small and accurate. It is used commercially in on-road vehicle safety equipment as well as the 'Segway' transportation device.

- The pressure in the tractor tires could be used as an indicator for overturn potential. The tire pressure is used as a surrogate to measure the forces on the wheels. This method needs calibration to obtain the tire pressures under no-load conditions. Although intuitive, it is cumbersome, insensitive and prone to errors when the tire pressure is changing under different temperatures. Also, when the operator changes the tire pressure purposely, the system needs to be recalibrated.

- The forces on the tractor axles can be measured in real time using load cells. This is a very direct measurement, which can also be applied in the case of the notorious backward overturn under high drawbar loads.

The latter method is proposed to be developed further in this research. Although there are technical hurdles, the force measurement is a superior method of overturn prediction. The forces on the wheels give a direct indication about the proximity to the overturn, well before it becomes apparent to the operator. The system can be used as a warning mechanism but it can also be used as input for an intervention system.

The following table gives an overview of the sensors that can be used under different potential overturn scenarios.

Table 1. Overturn scenarios, potential sensors and possible intervention methods.

		Warning devices	Automatic detection	Intervention methods
Gradual overturns	1	2	3	4
1	Hill slope lateral	Tilt sensor Force sensor	Tilt sensor Force sensor	Tire blowout, Anchoring, Arm deployment
2	Hill slope backward	Tilt sensor Force sensor	Tilt sensor Force sensor	Tire blowout, Anchoring, Arm deployment
3	High draft force backward overturn	Force sensor	Force sensor	Disengage clutch, apply brakes, disconnect drawbar
Sudden overturns				
4	High speed cornering		Gyroscope	Apply brakes
5	Obstruction collision		Gyroscope	
6	Lifted bucket		Force sensor	Drop bucket
7	Wheels stuck		Force sensor	Disengage clutch, brakes
Power hop				
8	Dry soils, high draft forces	Force sensor Gyroscope	Force sensor Gyroscope	Throttle down

The table is divided into gradual overturns and sudden overturns as well as a power hop scenario. The gradual overturn occurs when the tractor gradually becomes unstable (hill slopes) in a time period in which a human being is capable of reacting. A warning can be issued here and the operator can correct the situation. If the operator fails to correct the situation, the same sensor arrangement can trigger an active intervention method.

The sudden overturn occurs in such a short time period that a human is not capable of reacting. Only sensors and automatic recovery systems can bring the machine within the stable envelope and guarding mechanisms may be employed simultaneously.

The power hop scenario occurs under heavy drawbar loads combined with dry soils, usually during deep tillage like plow pan disruption. Power hop itself is not directly life threatening.

Column 2: Hill slopes represent a potential danger for overturning. The tilt sensor can be used in gradual lateral and gradual backward overturns as on hill slopes. It does not function in case of a high-drawbar force backward overturn since the tractor remains horizontal until it overturns violently and rapidly. This suggests that this case belongs in the sudden overturn category, but the overturn is only sudden in nature to the operator. The force sensor can definitely detect a gradual tendency to overturn, which puts it in the gradual overturn group. The force sensor does in all three cases work because it senses the loss of weight on the front wheels.

Warning devices are ineffective for sudden overturns, since there is no time for the operator to react. Only automatic intervention can prevent the overturn here. Automatic detection methods do not warn the operator but intervene when the tractor is about to turn over. All sensor types (tilt sensor, force sensor and gyroscope) are suitable for automatic detection under the three overturn scenarios.

Column 3: Automatic detection. In this case the sensors are part of an automatic intervention system that prevents the overturn.

Column 4: Possible intervention methods: gives some methods to prevent overturns such as the application of brakes and clutch, and more futuristic methods such as tire blowouts, stabilization arm deployment and anchoring. The methods mentioned here are not part of the research, but could serve as a starting point for active stabilization systems.

Row 6: The lifted bucket overturn is caused by a raised center of gravity combined with some external force due to lateral acceleration (steering) or acceleration/braking.

Row 7: A classic backward overturn scenario is a tractor which wheels are frozen stuck in the soil. This scenario overturns the tractor after starting the engine, engaging first gear and dropping the clutch. The events happen much too fast for a human being to intervene. Only automatic detection with a clutch depressing/braking action can prevent an overturn here.

Row 8: Power hop is a phenomenon that occurs in tractors with high power to weight ratios, under dry conditions with high draft forces (plow pan disruption). Although power hop is not necessarily a cause for overturns, the sensors will detect a harmonic motion of the machine. This will cause the force sensors to detect a negative value when wheels lose contact with the ground and they will activate a warning system. It is important that the automatic overturn prevention system distinguishes power hop from an imminent overturn. This is a difficult problem that needs to be further investigated.

Combinations of the causes are also possible for instance turning on a hill slope or hitting an obstacle while turning. For these reasons safety margins need to be established to take these combined dangers into account however unlikely they may be. The establishment of these safety margins will be part of the research activities.

Two examples will be given to show the merit of a force measurement system to detect the onset of an overturn. The first example is the backward overturn scenario, where the tractor is pulling a heavy load and the second is the gradual lateral overturn that may occur when the machine is used on a hill slope.

Example 1: High drawbar force backward overturn:

In this example, the drawbar pull is for simplicity assumed to be purely horizontal, the case gets slightly more complicated for angled pulls but the principle remains unchanged. It is assumed that the traction is sufficient to enable the drawbar force level. Only one side of the tractor is analyzed, since lateral symmetry is assumed.

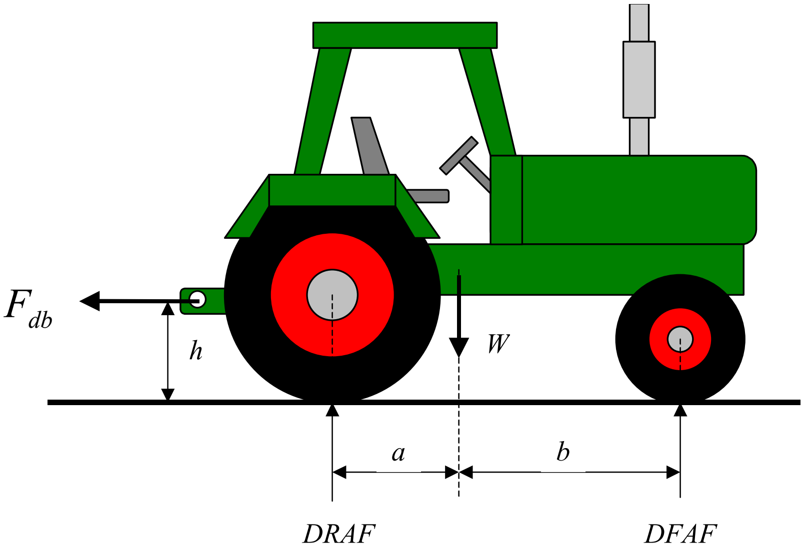

Figure 1 Tractor wheel loads due to horizontal drawbar pull

The force distribution of a tractor under a given tractor static weight and weight transfer is shown in Figure 1 where:

$DRAF$	Dynamic Rear Axle Force	$[N]$
$DFAF$	Dynamic Front Axle Force	$[N]$
F_{db}	Draw bar force	$[N]$
W	Tractor weight / 2 (lateral symmetry)	$[N]$
a	Distance from center of gravity to rear axle center	$[m]$
b	Distance from center of gravity to front axle center	$[m]$
$a+b$	Wheelbase	$[m]$
h	Drawbar height above the ground level	$[m]$

The force equilibrium for the tractor in Figure 1 is, taking the sum of the moments around the front tire soil contact point:

$$-DRAF*(a+b)+W*b+F_{db}*h=0 \qquad (1.)$$

and since

$$DRAF+DFAF=W \qquad (2.)$$

The dynamic (including weight transfer) forces on the front wheels $(DFAF)$ can be expressed by combining (1) and (2):

$$DFAF = W - DRAF = W - W * \frac{b}{a+b} - F_{db}\frac{h}{a+b} \qquad (3.)$$

or in shorter notation:

$$DFAF = \frac{W * a - F_{db} * h}{a+b} \qquad (4.)$$

The force on the front axle $(DFAF)$ is zero (or slightly negative due to the weight of the wheels) when a backward overturn commences. Equation (4.) shows that there is a linear approach to zero, when the force W, the drawbar force F_{db} and also the parameters a, b and h change, assuming that the combination $a + b$, (the wheelbase), remains constant. In contrast to a gradual lateral overturn like when driving on a hill slope, the operator cannot recognize the imminent danger of a backward overturn, since the tractor remains horizontal. For the same reason, a tilt sensor will not work; it can only work when the tractor is already leaning backward significantly.

In practice very high drawbar forces are combined with very high slip levels, which the operator might or might not respond to. However, under high traction operation the tractor may overturn and slip cannot be relied on as a safety net.

As an extreme case, during tractor pulls, even though the front wheels may be off the ground, very seldom a backward overturn occurs. This is partly because the hitching point is very low but also because the skilled operator can maintain equilibrium where enough slip is introduced to prevent the machine from overturning.

Example 2: Gradual lateral overturn:

A gradual lateral overturn commences when the line through the center of gravity surpasses the force line through the supporting down-slope wheel. In this case, the up-slope wheel does no longer carry a weight, which can be detected using the load cell arrangement as proposed. The force equilibrium under an angle is as follows (see Figure 2). The analysis was simplified by only taking into account the rear wheels. The left-hand image is the frontal view of the tractor, the center graph represents the force equilibrium triangle and the right-hand graph represents the forces during a lateral angle scenario.

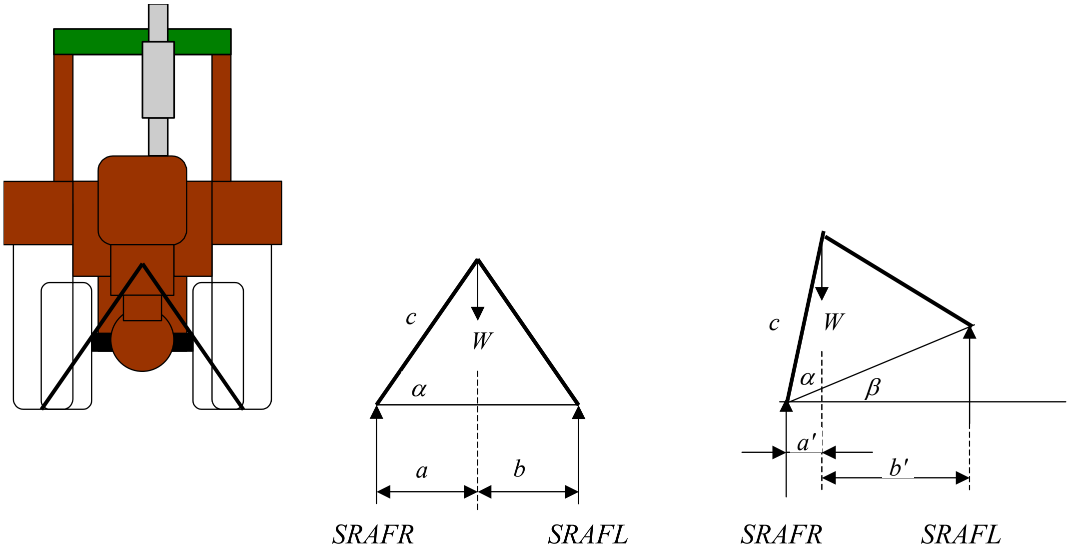

Figure 2 Forces on a tractor during a gradual lateral overturn

$SRAFR$	Static Rear Axle Force Right side	$[N]$
$SFAFL$	Static Front Axle Force Left side	$[N]$
W	Tractor weight	$[N]$
$a+b$	Tread width rear	$[m]$
c	Distance between soil contact point and center of gravity	$[m]$

Taking the sum of moments around the left wheel center gives:

$$Wb - SRAFR * (a+b) = 0 \tag{5.}$$

or

$$SRAFR = W\frac{a}{(a+b)} \tag{6.}$$

Since the sum of the vertical forces must equal zero:

$$W = SRAFR + SRAFL \tag{7.}$$

or

$$SRAFL = W\frac{b}{(a+b)} \tag{8.}$$

The distance between the center of gravity and the center soil contact point of the rear wheel (c) is assumed to be constant and therefore (see center graph):

$$a = c\cos(\alpha) \tag{9.}$$

In case of a hill slope, the original angle α becomes $(\alpha + \beta)$ (see right hand graph) and now:

$$a' = c\cos(\alpha + \beta) \tag{10.}$$

Substitution leads to:

$$SRAFR = W\frac{c}{(a+b)}\cos(\alpha + \beta) \tag{11.}$$

and

$$SRAFL = W - W\frac{c}{(a+b)}\cos(\alpha + \beta) = W\left[1 - \frac{c}{(a+b)}\cos(\alpha + \beta)\right] \tag{12.}$$

When $(\alpha + \beta) \geq 90$ degrees, the tractor will overturn laterally. The resulting forces on the wheels are not linear with the angle β itself. However a cosine behavior is also predictable and near-linear in the operating range, as in the backward overturn case from Example 1.

As in the backward overturn case, there are situations where two wheels may be off the ground and the vehicle does not overturn. A good example is stunt drivers who steer a car on two wheels like a motorcycle. This is obviously a situation that needs to be prevented at all cost in safe agricultural practice.

Another dangerous mode is that the machine will start sliding down the hill slope and then potentially overturns for example when hitting a ditch. The method as proposed here, is not suitable to predict the potential for sliding, since it does not measure the friction characteristics of the tire-soil interface.

Objectives

1. The first objective is to develop a remote controlled ¼ scale tractor model to demonstrate the concept of adaptive rollover detection system using load cells and an electronic data acquisition system.

2. The second objective is to develop a computer model in ADAMS to simulate the overturns that will be demonstrated in real life.

3. The third objective is to use the ¼ scale tractor model to validate the ADAMS computer model.

Research methodology

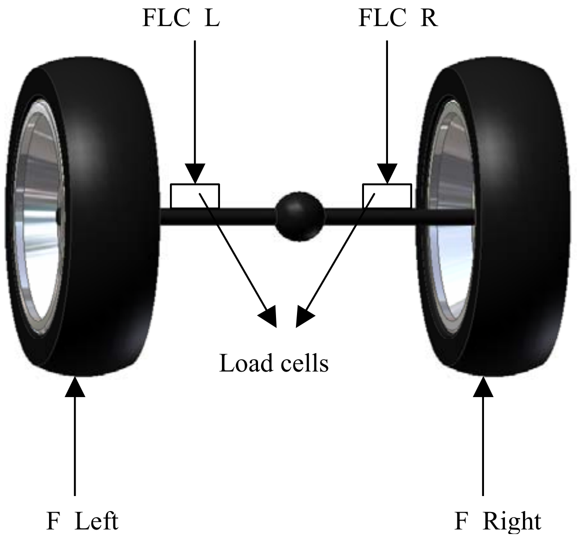

Figure 2: Load cells mounted on axles

The load cells need to be specified in the expected force range and mounted in the axles of the tractor. The most promising type is the S-type as shown in Figure 3.

A rugged computer system will be used to monitor the load cell outputs in real time. Software will be developed to distinguish between overturn modes (including power hop) and the transient pulses generated by sudden collisions with obstacles.

As shown in the previous examples, the imminence of overturns can be detected by monitoring the forces acting on the wheels of a tractor. A ¼ scale rear wheel drive tractor will be developed that is suitable for all types of possible overturns such as lateral and backward hill slopes, high drawbar force backward overturns as well as a lifted bucket overturn. A Briggs and Stratton 16 hp engine, as used in the ASAE ¼ scale tractor competition, will power the tractor.

The power hop scenario cannot be emulated in practice, because the power to weight ratio of the tractor is not high enough. However, a vibration platform will be built to simulate this behavior.

The tractor will be completely remote controlled using a wireless connection. Safety features will be built in to prevent a runaway tractor scenario.

Figure 3. S-Type load cell

Figure 4. IDAN computer system

The computer system must be very rugged, since the tractor will be used to demonstrate real life overturns with the accompanying acceleration forces. The proposed data acquisition computer system for the project is a PC104 model, fitted in an aluminum casing (IDAN, Real Time Devices Inc. State College, PA) as shown in Figure 4. This unit is very compact and does not need external cooling. It is mounted on an shock proof plate meeting MIL-S-901 lightweight Grade B Navy high impact shock test requirements as well as crash safety requirements of MIL-E-5400 (30g 11 millisecond half-sine pulse shock).

The IDAN computer system can be fitted with a Controller Area Network (CAN) card. This is a two-wire intra vehicle network that is very suitable for dynamic data acquisition systems and rapidly becoming a standard in the US for off-road vehicles. The main advantage of this system is that changes can be made to the sensor layout without changing any wiring. An additional sensor can be added which announces itself to the network and from that point forward becomes an integral part of the data acquisition system.

Measuring the weight of a tractor in real time is not a trivial task. There are many forces acting on wheels/axles during operation such as dynamic weight changes, which occur when a tractor accelerates/decelerates, when it hits an obstruction (which generates a spike-type transient pulse), when a tractor drives around a corner (centripetal forces) and in the most extreme case, under power hop conditions.

- Acceleration and deceleration forces are not suspect to causing overturns due to the high weight and small acceleration of tractors. The forces during acceleration and deceleration are easily recognized due to the lateral symmetry. If an acceleration / deceleration causes a wheel to lift off the ground, the system will properly detect it as an overturn and can react by eliminating the acceleration (throttle down or release brakes).

- When the tractor hits an obstruction, the force on the wheel first becomes large and then small (or negative if the wheel loses contact with the ground). This scenario is unique enough to be distinguished from a gradual overturn due to hill slopes or high center of gravity operations such as a raised bucket overturn. Another potential problem is when a tractor is already unstable on a slope and an obstruction is hit. There needs to be enough safety margin in the system to not overturn the tractor in this case. The magnitude of this margin needs to be determined as part of this research.

- A wheel lifting on the inside of the turn accompanies cornering overturns. This scenario cannot be distinguished from a hill slope or raised bucket overturn and the system will detect it properly as a potential overturn. An active intervention system can slow the tractor down to prevent an overturn.

- In the power hop case, load cells can detect the typical harmonic motion of the tractor and generate a warning that power hop is imminent, even though the operator might not detect its onset. Power hop generates such an uncomfortable ride that the operator is not expected to maintain this situation and will throttle down to stabilize the machine. Active intervention systems may do this automatically.

Overturn simulations will be carried out in ADAMS, the world's most widely used mechanical system simulation software. The tractor will be modeled in ADAMS and computer experiments carried out to design the field tests.

Dr. Tony Grift has extensive experience in off-road data acquisition systems and software development. He will be responsible for the managing the building of the tractor, the experiments and data analysis, development of electronic systems, technology transfer and overall project management.

Matt Veal has worked extensively with off-highway vehicle overturns in an attempt to develop improved industry ROPS standards. He has broad experience with modeling machinery safety in ADAMS and NASTRAN and he will carry out simulations and model validation using the proposed ¼ scale tractor.

Expected outcomes/contribution to field

The outcome of the research is a system that can detect the imminence of overturns for the practical situation where the load on the tractor changes and the geometry as well (raised bucket). Other methods need to be calibrated and cannot deal with changing loads. The experimental results will show that the proposed method is a direct and effective way of predicting overturns. It will hopefully encourage manufacturers to develop load cell systems that are integrated in tractors for safety purposes.

The research will also yield a remote controlled ¼ scale tractor model that can be used for overturn demonstration purposes at agricultural shows and other meetings. It will be used to generate public awareness of the importance of ROPS and the use of seatbelts.

The proposed research can be used as a basis for further development of systems that prevent overturns altogether. Actuation methods need to be developed in first instance using systems already present on tractors such as clutch actuation to disconnect the power train during a backward overturn and active braking to stabilize the tractor during a sharp turn.

Advanced rollover prevention systems can be researched such as tire blowout, stabilization arm deployment and even ground fixation using a machine anchoring technique. All these methods need an early warning system that is reliable, does not cause false alarms and does not depend on geometry changes and weight shifts. The Adaptive Tractor Overturn Prediction System (ATOPS) is an excellent basis for these methods, since it supplies a direct measure for the proximity of the overturn occurrence, rather than detecting its occurrence after the fact.

The proposed research is intended as a starting point to continue developing sensor-based inherent safety features on tractors. Tractor overturns may be the most prominent cause of death on farms, however, (enforced) retrofitting older tractors with ROPS can prevent most of these. Other causes of death are tractor runovers, entanglements and road accidents. Some examples of where technology can be used to prevent accidents and make the farm operation safer are:

- Using infrared sensors to detect the presence of humans around the tractor can prevent runovers. The infamous jump-start runover can be easily prevented by a simple mechanism that does not allow the engine to start when the gear is engaged and the handbrake is off.

- Entanglements during hitching can be prevented by automating the process, so the operator can stay on the tractor.

- Having slow moving vehicles broadcast a signal that allows other road users to identify the machine on their GPS guidance screens can reduce roadway accidents.

In first instance, actuators that are already on tractors can be used such as brakes and clutch as safety devices. For example, the force sensors as proposed could be used to slow a tractor down using the brakes when the operator is negotiating a sharp corner that may overturn the tractor. The clutch can be disengaged when a backward overturn is imminent.

There are additional benefits to using force sensors as proposed. By knowing the forces that act on the wheels at all times, the traction of the tractor can be optimized and energy saved. This example shows that the development of sensors and especially combinations of sensors can contribute to safety, energy efficiency, environmental impact and economic gain.

The results of this research will be used to leverage more funding from sources such as USDA and the University of Illinois Research Board. Also, Illinois-based equipment manufacturers such as John Deere, CASE and Caterpillar will be contacted to collaborate on this research through technical and financial support.

Timeline

June 03
- Building the framework for a two wheel drive tractor
- Selecting load cells, data acquisition system and remote control hardware

July 03
- Start building data acquisition system
- Developing software for data-acquisition
- Mounting load cells on frame

August 03
- Developing CAN software for interfacing
- Testing data acquisition system
- Mounting wheels and steering / brake components

September 03
- Mounting engine and drive train components
- Testing remote control systems

October 03
- Mounting electrical and auxiliary systems

November 03
- Mounting Roll Over Protection System on tractor
- Testing software components

December 03
- Mounting remote control hardware
- Testing complete tractor

January -March 04
- ADAMS Simulation model development

April-May 04
- Building of test track
- Field experiments

May 04
- Model validation using field data
- Final reporting and publication

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Education:

Ph.D.	Agricultural Engineering, University of Arkansas	1998
M.Sc.	Agricultural Engineering Wageningen University, The Netherlands	1992
B.Sc..	Industrial Automation, Utrecht Polytechnic School, The Netherlands	1987

Professional Experience:

Assistant Professor	Dept. of Agricultural Eng., UIUC	2002-present
Assistant Professor	Dept. of Biosystems Eng., Auburn University	1998-2002
Graduate Research Asst.	University of Arkansas	1995-1998
Research Engineer	Wageningen University, The Netherlands	1993-1995
Systems Engineer	Vertis Information Technology, The Netherlands	1992-1993
First Lieutenant Instructor	Royal Dutch Airforce, The Netherlands	1987-1989

Honors and Awards:

2002 ASAE Superior Paper Award	American Society of Agricultural Engineers

Selected Recent Publications

Refereed papers:

Grift, T.E. 2003. Fundamental Mass Flow Measurement of Solid Particles. *Particulate Science and Technology* 20(1) XX-XX

Grift, T.E., and J.W. Hofstee. 2002. Testing an Online Spread Pattern Determination Sensor on a Broadcast Fertilizer Spreader. *Transactions of the ASAE*. 45(3):561-567

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Publication Summary:

Journal articles: 12
Proceedings articles: 6
Technical reports: 6

Matthew Veal

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Education:

M.Sc. Mechanical Engineering, Auburn University, Auburn, AL 2003
B.Sc.. Forest Engineering, Auburn University, Auburn, AL 2001

Professional Experience:

Graduate Teaching Assistant. Dept. of Biosystems Eng., Auburn University, AL 2002

Honors and Awards:

JBT Scholarship award, University of Illinois, 2003
Council on Forest Engineering Student Communication Award 2002
Auburn University Presidential Fellowship 2001
Forest Engineering Student of the Year 2001
ASAE Preprofessional Poster Competition – First place, 2000
Fort James Forestry Student Mathematics Award 2000

Selected Recent Publications

<u>Proceedings and Meeting Papers:</u>

Veal, M.W., S.E. Taylor, R.B. Rummer. 2002. Development of a Test Device for Evaluation of Thrown Object Hazards ASAE Technical Paper No. 02-8037. ASAE, St. Joseph, MI.

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Publication Summary:

Journal articles: 0
Proceedings articles: 6
Technical reports: 0

Budget

PI	Dr. Tony Grift	Dept. of Ag. Engr.
Co-PI:	Matthew Veal	Dept. of Biosystems Eng.

Summary

Salaries and Wages			
	PI: Grift		7,167
	Co-PI Veal		4,000
	Total salaries & Wages		**11,167**
Fringe Benefits			
	PIs - Grift	28.71%	2,058
	Co_PI	0.01%	0
	Total salary Wages, Fringe		**13,224**
Equipment			
	Load cells		1,300
	Total equipment		**1,300**
Total Direct Costs			**14,524**
	TMDC		**13,224**
Facility & Adminstration Fees		**8%**	**1,058**
	Total Project Costs	**TDC+FA Fees**	**15,582**

Budget justification

Personnel

Salary of a month is requested for the PI, in which he will manage the project and disseminate the results. Additional funds are requested for Co-PI Matt Veal, to cover his salary above his Jonathan Baldwin Turner (JBT) scholarship funding.

Fringe Benefits

Fringe benefits are requested in accordance with the guidelines of UIUC being 28.71% for the PI and 0.01% for graduate students.

Equipment

Funds are requested for the load cells. The materials needed to build the ¼ scale tractor are available from previous competition tractors. The ruggedized data-acquisition computer will be funded through hatch funds. The ADAMS software is available on campus.

Indirect costs

Indirect cost are requested in accordance with the guidelines of 8%.