Testing and Creation of a Safety System to Disengage the PTO of a Tractor

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Abstract. *Production agriculture consistently ranks as one of the most dangerous U.S. industries. As a result, significant research has been devoted to reducing the number of agricultural injuries and deaths. This study involved the design and testing of a safety sensor system using off-the-shelf security sensors to detect people in the power take-off (PTO) hazard area between a self-unloading forage wagon and a tractor. A total of 288 tests with four different sensor technologies explored the reliability of human presence security sensors for operator detection. Test data were statistically analyzed to determine how the sensor technology, approach angle, and mounting height affected the distance of a person from the hazard at the time of detection. After sensor tests were completed, a working prototype shut-off system was created to disengage the PTO of a tractor if a person entered the PTO hazard area, causing the PTO to stop rotating. The shut-off system also sounded an audible alarm and initiated flashing of a strobe light after detection, signaling that a person had entered into the PTO hazard area.*

Keywords. *Safety, Injury, Sensor, Human presence detection, Entanglement.*

I n 2003, agriculture was ranked by the National Safety Council as the second most dangerous U.S. industry, with 20.9 deaths per 100,000 workers. Total work-related deaths were estimated to be 710 persons per year (National Safety Council, 2004). Detailed annual data related to specific causes and agents of injury are not always available. In a review of existing agricultural fatality and injury data, Thomas and Buckmaster (2003) reported that there are approximately 12 power take-off fatalities per year based on National Safety Council data, and a projected 2200 severe or permanent PTO-related injuries annually.

When and how injuries have occurred has been documented. In one 1987 study at Purdue University, 50% of PTO injury cases involved stationary equipment, and another 28% involved semi-stationary equipment (Campbell, 1987). Nearly all incidents that involved a PTO occurred while the equipment was in a stationary position and the PTO was engaged. Using this information, it would seem desirable to develop and demonstrate a sensor-based system with the system's primary function being to detect people within the PTO hazard area while the tractor is stationary with the PTO engaged.

Rotating shafts, specifically a PTO, while functional and efficient, pose a serious hazard to persons who encounter the rotating hazard. To reduce this hazard, potential solutions could be 1) to not allow people near a PTO or, 2) use a non-PTO design to transfer power. Due to the function and operation of some farm machinery or the use of older machinery, tasks still require a person to be present near a PTO. An example is a self-unloading forage wagon. Removing the PTO hazard entirely is another option. For example, replacing the PTO with a hydraulic drive system for a self-unloading forage wagon would reduce the rotating component hazards, but replacement options are not always feasible or energy efficient. Also, stored energy hazards would still be present.

This research investigated technologies to detect people in hazardous areas near a tractor's PTO, using low-cost, off-the-shelf security sensors integrated into a safety sensor system. The goal was to work toward a sensor system that might be added to existing equipment and incorporated into new equipment. The system designed in this work also provided the ability to shut off the PTO when a person entered the hazardous area.

Literature Review

Much research has been done to apply safety sensor technologies to real-world problems. Mining, construction, automotive, and agriculture are examples of industries that use sensor technology for human presence detection, safety devices, and collision avoidance. Following is a review of current sensor research within these industries.

Mining and Construction

In the mining and construction industries, sensor systems to detect people in hazard areas have been tested and used for some time. In 1988, the Bureau of Mines tested a system to detect objects in the rear area of front-end loaders and to notify the operator of their presence to prevent backovers (Laage et al., 1988). The system used ultrasonic and Doppler radar sensors and sounded a backup alarm when an object or person was within 15 to 25 ft of the rear of a front-end loader.

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Following this early research, Leger et al. (1998) demonstrated the use of a rotating reflector and distance-measuring sensor to detect obstacles within the working area of a hydraulic excavator. This work predicted the motion of the excavator and halted operation if an object was detected in the hazard area.

In addition to motion or object identification systems, Schiffbauer (1999) used wire loops that generated low frequency magnetic fields to define the contour of the danger zones around an underground coal-mining machine. Preliminary testing demonstrated a successful system, but bystanders were required to wear a receiver to be protected.

Stentz et al. (1999) developed an automated 25-ton hydraulic excavator that successfully loaded trucks at speeds that were comparable to an expert operator. The system used two scanning laser range finders and motion planning software. The system extrapolated the excavator's motion several seconds ahead of actual movement and compared this to sensor data to determine if there would be a collision with a person or object. If a collision was predicted, the excavator was designed to stop immediately.

In a test of commercially available collision and detection sensor components, Boldt et al. (1999) tested off-the-shelf Doppler radar alarm units, a radio frequency identification (RFID) tag system, and a closed circuit television (CCTV) system. All three technologies proved viable, with the CCTV system successfully working through a year's testing. The Doppler radar units required frequent, time-consuming adjustments to reduce false alarms.

Additional testing of radar and RFID systems on mining trucks was done by Ruff (2000), providing further evidence of the potential of both technologies. Findings indicate that to determine if vibrations or signal reflections adversely affect the system, tests should be on the actual vehicle while the vehicle is moving toward the object. Further, the actual object to be detected should be used in research tests since many collision-warning systems are sensitive to characteristics of the detected object.

In 2001, Ruff continued sensor research with low-cost radar-based collision-warning systems. The recommendations of these tests were to perform experiments on the actual equipment because system characteristics vary depending on the mounting height and physical characteristics of the vehicle. It was also recommended that a secondary system be used with radar to prevent false alarms.

In 2002, Ruff showed that the maximum range or outer dimensions of the detection zone are not affected by a person's height, but are affected if the system is mounted higher than approximately 1.8 m above the ground. Mounting sensors above 1.8 m allowed the person to walk under the radar beam. Additional recommendations were:

- A person of average height (1.75 ± 0.08 m) should be selected as a test subject to determine the detection zone of a person.
- Radar systems should be mounted at approximately chest height for best detection.
- After installing a collision warning system, the equipment should be moved in reverse (or forward for front-mounted sensors) in an area with no obstacles or people present to determine if false alarms occur.
- The reliable detection zone for a person should be determined by having a person walk toward the stationary equipment while it is running,
- The reliable detection zone should be verified by moving the equipment toward a stationary standing person.
- The reliable detection zone for a smaller vehicle should be determined by moving the equipment toward the parked vehicle in different locations.

Through this research in mining and construction, many sensor technologies have been researched and a preliminary method for mounting and testing sensors has been established.

AUTOMOTIVE

Within the automotive industry, sensors have been applied to the detection of objects in front of cars and also incorporated into onboard safety sensors. In 1995, Chang et al. presented test findings of a prototype, autonomous, intelligent cruise control system using radar mounted to the front grill of an automobile. The radar tracked targets at distances greater than 100 m, but target range resolution decreased at longer distances. The sensor automatically adjusted the vehicle speed to maintain a constant, safe following distance from a lead vehicle on a closed loop track.

Curio et al. (2000) suggested a method for the detection and tracking of pedestrians crossing in front of automotive traffic using a gray scale CCTV camera. These images were analyzed by texture, patterns of movement, and model-based groupings of features most likely belonging to a pedestrian to determine if a person was crossing in front of the vehicle.

In addition to people detection, a real-time deformation rate crash sensor, based on a 6-GHz active integrated antenna, was developed and verified through realistic crash tests by Kaleja et al. (2000). The system proved capable of detecting a side impact within a few milliseconds and could also forecast the characteristics of the crash to coordinate different passenger protection devices.

In addition to published research, collision-warning systems are now being incorporated onto vehicles and sold as an aftermarket attachment. Delphi Automotive Systems (Troy, Mich.) has developed a system that adjusts cruise control through the use of radar or laser sensors. These units are effective at speeds greater than 20 mph. Delphi also offers a reversing aid using radar that monitors distance and speed, ad provides a detection range of six meters behind a vehicle (Delphi, 2002). General Motors (Detroit, Mich.) offers thermal imaging on Cadillac automobiles that assists drivers in nighttime or reduced visibility driving and also offers a reversing ultrasonic sensor system that aids with parking (Cadillac, 2002).

AGRICULTURE

Within the agricultural sector, much work was completed in the late 1990s in efforts to detect various hazards including roadway collisions as well as sensing people near rotating agricultural machines. Shutske et al. (1997) designed and tested an agricultural vehicle collision avoidance system using microwave sensor technology. The sensor performed well when mounted on a stationary or very slow moving agricultural vehicle, but field applications produced inadequate detection distances, with the recommendation that the system tested did not have sufficient range.

Additionally Shutske et al. (2001) reported testing a multi-sensor detection system to protect persons from entanglement in a PTO. Off-the-shelf passive infrared, radar, and microwave security sensors were tested in 822 warm

weather tests with no reported system "misses." This system yielded warning times of 0.5 to 1.0 s (distance from the hazard at the time of detection divided by the approaching person's velocity). The warning time is the true window of opportunity available for moving component shutdown at the instant that the person is detected. The use of dual sensing technologies suggested a reduced frequency of false alarms and missed detections. No system to shut down the PTO was developed as part of this work.

In 2000, White et al. developed a hydraulic circuit to replace a rotating PTO by using hydraulic power to operate a rotary field mower. Initial testing allowed the emergency stopping of the mower blade in 0.33 to 0.77 s, but inefficiencies associated with the use of hydraulically driven systems presented problems that could limit the use of fluid power as a replacement for PTO's. This work discussed the application of infrared sensors near the tractor seat to create an operator presence sensing system, but no sensor trials have been published.

A safety detection system utilizing two ultrasonic sensors to detect a moving object and to determine its position around agricultural machinery was reported by Guo et al. (2002). The sensors provided 15 degrees of visual detection and human walk testing demonstrated the system's feasibility below specified voltage outputs.

METHODOLOGY

The specific goals of this work were 1) to test current sensor technologies and determine their effectiveness, 2) to determine how mounting height and angle of approach affects the sensor system, and 3) to create a functioning prototype system that shuts off the PTO when a person enters the hazard area.

To achieve these goals, four off-the-shelf human presence security sensors (table 1) were chosen to allow comparison between varying sensor technologies. At the time this study was conducted, Sentrol (Tualatin, Ore.) was the only company to offer radar as a security sensor technology. Using all sensors from a common manufacturer was believed to reduce variability in the results. The Sentrol AR435 was used for two separate tests because the passive infrared could be turned off.

The agricultural machine used was Meyer's Mfg. Corp. 518 SF (Dorchester, Wis.) self-unloading forage wagon attached to a John Deere 6400 (Deere & Co., Moline, Ill.) tractor rated at 85 PTO hp. This equipment combination was selected because it was readily available at the research site. This size of tractor was also typical of tractors involved in entanglements that can occur when used with forage implements, grain augers, and rotary mowers. The particular forage wagon was again chosen based on availability and because it represented a stationary application of a PTO-driven machine.

The wagon was approximately the same width as the test tractor (as defined by the outside edges of the tractor's tires), offering a rectangular hazard area between the tractor and forage wagon. An assumption of this research was that the use of a self-unloading forage wagon represented many of the diverse environments encountered within an agricultural application.

The sensor system tests were done in the fall with ambient air temperatures between 17.8°C and 18.9°C. During testing, the tractor's engine was running at 1000 rpm. The PTO was connected to the tractor, but was not operating due to the hazards associated with walking toward and working near a revolving PTO as test subjects approached. The tractor and wagon were parked on a gravel driveway believed to be representative of a location where a stationary PTO operated implement would be used. The test subject was a 1.80-m, 73-kg male wearing jeans, t-shirt, light jacket, and boots. The physical attributes of the test subject and clothing worn had been shown previously to not effect sensor system performance and were not further explored (Shutske et al., 2001; Ruff 2002).

Sensor heights of 1.73 m (low), 2.16 m (middle), and 2.59 m (high) from the ground were selected for the placement of the sensors (fig. 1). To achieve the different heights, 0.91-m drawer slides were fixed to the rear of the tractor to allow quick movement between each of the three height settings. The high and low levels were chosen to maintain visibility for the tractor operator and to determine how sensor performance changed as height varied.

Due to the sensors having a quarter-circle detection pattern, each sensor was adjusted prior to the tests to have the same coverage area according to the specifications supplied with the sensor. With each sensor set at the low height level, the mounting angle was adjusted so the coverage area for all the sensors would be a quarter-circle with a radius of 2.54 m. This area was selected because it was the approximate distance from the mounted sensor to the outside edge of the tractor tire on the opposite side, allowing a coverage area within the outside edges of the back tractor tires. This coverage area allowed the operator to walk adjacent to the tractor and implement without causing a false alarm.

The sensors were placed 0.70 m out from the center of the tractor, behind the tractor's ROPS to increase operator visibility and protect the sensors from branches, mud, and other material that would be encountered during operation. Horizontal placement of the sensors was held constant.

Table 1. Sensors used for walk testing.

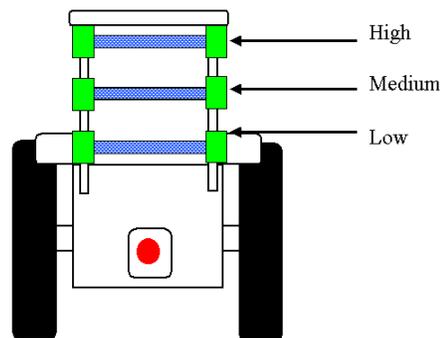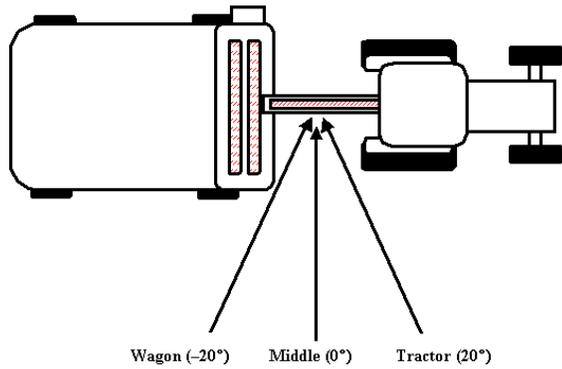| Sensor Model	Technology the Sensor Uses
Sentrol AR435	Radar and passive infrared
Sentrol 2T40	Microwave and passive infrared
Sentrol 6155	Passive infrared
Sentrol AR435	Radar only (passive infrared disabled)

Figure 1. Sensor heights used for testing.

Figure 2. Approach angles used for testing.

Approach angles of –20°, 0°, and 20° relative to the hazard (fig. 2) were selected to determine performance of each sensor. These approach angles simulated a person approaching the PTO from the wagon or implement, from the middle as if coming from another task, and from the tractor to simulate a person dismounting the tractor and approaching the PTO.

Because of the challenges in determining the optimum mounting height and affects of approach angle on each sensor, a matrix was created to evaluate all possible combinations of sensor technology categories, sensor heights, and operator approach angles. This approach was applied to allow the research team to quickly and effectively test different configurations in an organized manner. Eight replications were performed for each matrix cell, allowing a completely randomized $4 \times 3 \times 3$ factorial design with sensors being a blocked variable for statistical analysis to aid in determining the optimum sensor technology and configuration.

To test sensor performance, a modified version of the data acquisition system created by Shutske et al. (2001) was used (fig. 3). The system included LabVIEW (National Instruments, Austin, Tex.), version 6.0 software a National Instruments 6024E PCMCIA data acquisition card, and a Dell (Round Rock, Tex.) 700-MHz Inspiron laptop computer. Sensor scanning rate was set at 20 Hz. No additional signal filtering or conditioning was incorporated into the system.

A total of 288 walk tests were performed with the subject's position recorded at the time of detection using a DVT-500-A displacement/velocity transducer (PSI-Tronix Technologies Inc., Logan, Utah). This unit allowed for the measurement of distance from the hazard at the time of detection as well as approach speeds of the test subject as they walked toward the hazard. The distances from the test subject to the hazard were recorded using a program created in LabVIEW 6.0 from National Instruments.

After field testing, ANOVA was used for statistical analysis. A mean detection distance (distance from the person to the hazard) at each configuration was calculated to determine where a person would likely be detected.

After sensor tests were complete, a prototype automatic shut-off system was designed and constructed to allow the PTO to be disengaged when a person entered the hazard area.

The shut-off system that was designed used a DirectLogic 105 (AutomationDirect, Cumming, Ga.), programmable logic controller (PLC) for processing inputs and determining
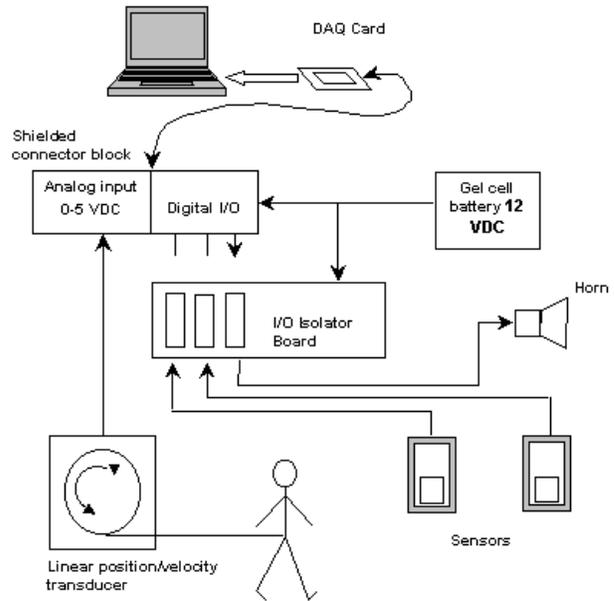

Figure 3. System used to test the varying sensor technologies and configurations.

outputs. A ladder logic program for the PLC was created using DirectSOFT32 version 3.0 software (AutomationDirect, Cumming, Ga.). This system (see fig. 4) connected to the PTO switch and did not activate the sensor system unless the PTO was engaged. A limit switch was attached to the shifting lever, further requiring that the tractor be in park before the system was enabled.

When these two criteria were met (PTO engaged and tractor in park), the system was active. If a person entered the hazard area protected by the sensors, the sensors triggered, causing the PTO solenoid to redirect hydraulic fluid from the PTO clutch to the PTO brake, stopping the PTO. At the same time, a horn and strobe light provided an audible and visual warning, signaling that a person entered the hazard area. After a detection and shut-off event occurred, a red pushbutton lit up and needed to be pushed to reset the system.
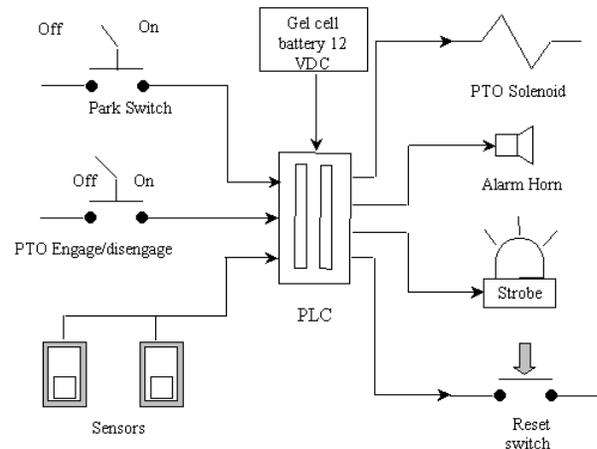

Figure 4. Diagram of the sensor system created to shutdown the PTO.

Table 2. ANOVA based on distance from hazard (cm) at time of detection (α = 0.05).

Source of Variation	Sum of Squares	df	Mean Square	F	p-value	F Crit
Sensor (blocked)	540,703	3	180,234	145.94	.0000	2.64
Height	129,621	2	64,811	52.48	.0000	3.03
Approach	62,129	2	31,065	25.15	.0000	3.03
Sensor × height	358,289	6	59,715	48.35	.0000	2.13
Sensor × approach	46,021	6	7,670	6.21	.0000	2.13
Height × approach	20,265	4	5,066	4.07	.0031	2.41
Sensor × height × approach	32,717	12	2,726	2.21	.0119	1.80
Error	311,286	252	1,235			
Total	1,501,031	287				

The design required that the PTO switch be turned off and on again to allow for the PTO to be engaged.

Results

Field Testing

The 288 walk tests were analyzed using SPSS version 10 (Chicago, Ill.). The critical variable that was analyzed was the distance from the person to the actual hazard at the time of detection. Statistical methods recommended by Neter et al. (1996) for the analysis of a completely randomized three factorial design with one variable blocked were used. ANOVA results are summarized in table 2.

Test results indicated that all factors examined (sensor type, sensor height, and approach angle) were statistically significant. The large F value for sensor type (blocked) suggested that each sensor technology tested performed very differently from each of the other sensors tested, as would be expected. This meant that when a sensor-based system is designed, the selection of the type of sensor technology is critical and must consider the range of environmental and operational conditions likely to be encountered during normal operation.
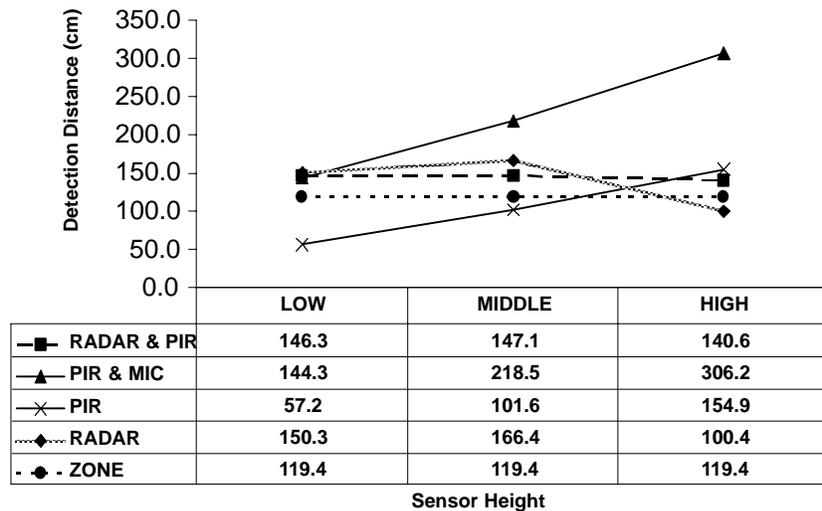
Table 2 shows the F value for sensor height was twice that of the approach angle. This indicates that the height at which a given sensor type is mounted is a critical design variable as compared to the angle at which the sensor is approached. Stated another way, if the sensor's height is correctly placed during the design process, then the sensor is more likely to perform satisfactorily when the hazard is approached from multiple angles. This finding was further reinforced by examining the interaction between sensor type and mounting height which had an F value approximately eight times larger than that of the interaction between sensor type and approach angle.

Since the effect of approach angle was minor relative to mounting height, all data from the three approach angles were combined for each sensor and height configuration. The combination of approach angle data allowed comparison between the detection distance for different sensor and height combinations (fig. 5). The line on figure 5 labeled "zone" (constant at 119.4 cm) represents a straight line projected backwards from the outside edge of the tractor's tires and represents the threshold distance between where detection is desirable and undesirable. Detection distances below the zone line were inside of the desired hazard area (too close to the hazard) while distances above the zone line were outside the hazard zone. Note that it is not desirable to detect too far outside the hazard zone, because this will likely lead to a higher rate of system false alarms.

Radar/PIR

The radar/PIR sensor was relatively unaffected by mounting height as is indicated by the smallest deviation from a straight line between heights in figure 5. The radar/PIR sensor would allow the system designer more mounting height flexibility without compromising sensor performance. The independence between mounting height and detection

	LOW	MIDDLE	HIGH
—■— RADAR & PIR	146.3	147.1	140.6
—▲— PIR & MIC	144.3	218.5	306.2
—✕— PIR	57.2	101.6	154.9
···◆··· RADAR	150.3	166.4	100.4
- ● - ZONE	119.4	119.4	119.4

Sensor Height

Figure 5. Mean detection distance for sensors after approach angles were combined.

distance was partly due to the range control feature of this sensor, which allowed the range to be selected as 2.7, 5.5, 8.2, or 10.7 m, with the 2.7-m setting used for testing. The radar/PIR technology reduced the drop in the detection distance at the high height setting when compared to the radar sensor. The optimal height for the radar/PIR sensor was the middle height, with a standard deviation of 23.7 cm as is shown in table 3.

PIR/MICROWAVE

The PIR/microwave sensor showed a linear relationship with detection distance increasing as sensor height increased (fig. 5). Additional research is needed to determine if there is a relationship between the combined approach angles and height. The smallest standard deviation for this sensor was 30.2 cm with the sensor at the low height.

PIR

The PIR sensor also showed a linear relationship between sensor height and detection distance (fig. 5). Analysis of mounting height versus approach angle does agree with this linear relationship, but further testing is needed to determine why such a strong correlation exists between sensor height and detection distance. The middle height setting provided the smallest standard deviation of 43.0 cm.

RADAR

The radar sensor provided an adequate hazard area coverage at the low and middle height settings, but did not detect consistently at the high mounting height (fig. 5). This drop is thought to have been caused by the test subject walking under the detection zone before detection occurred, similar to what was documented by Ruff (2002) in the mining tests that were discussed earlier. This could present barriers for future designers, since it would seem desirable to have a sensor mounted high to avoid getting it caked with mud or damaged by debris from the tractor's tires or other sources. The standard deviation for all three approach angles combined at the low height setting was 15.4 cm, which is the lowest standard deviation for all sensors. The standard deviation at the other two heights was approximately twice that of the low height setting.

PERFORMANCE TEST SUMMARY

Based solely on standard deviations, the radar and radar/PIR sensors showed the most consistency in performance as a result of lower standard deviations. A Tukey's test was conducted using SPSS Version 10 to determine if the sensor means were significantly different. This test revealed that the means of the radar/PIR sensor and the radar sensor were not significantly different at the 95% confidence level.

To further compare and explore the sensor performance, confidence intervals (CI) and prediction intervals (PI) were calculated for each sensor using the sensor height configuration that resulted in the lowest standard deviation with the approach angles combined. For example, with the radar/PIR sensor, the middle height detection distance mean (147.1 cm) and corresponding standard deviation (23.7 cm) were used to calculate the CI and PI.

Since the radar sensor had the lowest SD, this sensor provided the smallest range for the CI and PI at 14.9 and 74.5 cm, respectively. However, even though the radar

Table 3. Detection distances and standard deviations for each sensor, height, and approach configuration (con't).

Sensor	Sensor Height	Approach Angle	Mean (cm)	Std. Dev. (cm)	N
Radar and PIR	Low	Tractor	117.1	32.8	8
		Middle	172.6	6.8	8
		Wagon	149.3	14.6	8
		Total	146.3	30.8	24
	Middle	Tractor	128.7	26.1	8
		Middle	162.9	11.9	8
		Wagon	149.8	18.4	8
		Total	147.1	23.7	24
	High	Tractor	125.8	3.0	8
		Middle	160.1	43.6	8
		Wagon	136.0	17.4	8
		Total	140.6	29.8	24
	Total	Tractor	123.9	23.7	24
		Middle	165.2	25.8	24
		Wagon	145.0	17.4	24
		Total	144.7	28.0	72
PIR and Microwave	Low	Tractor	134.1	11.3	8
		Middle	177.9	14.1	8
		Wagon	120.7	25.1	8
		Total	144.3	30.2	24
	Middle	Tractor	170.5	10.0	8
		Middle	274.6	22.9	8
		Wagon	210.4	19.9	8
		Total	218.5	47.2	24
	High	Tractor	323.4	33.0	8
		Middle	322.1	60.0	8
		Wagon	273.1	35.0	8
		Total	306.2	48.7	24
	Total	Tractor	209.3	86.1	24
		Middle	258.2	71.2	24
		Wagon	201.4	69.0	24
		Total	223.0	78.9	72
PIR	Low	Tractor	35.4	23.6	8
		Middle	104.2	32.6	8
		Wagon	31.9	36.3	8
		Total	57.2	45.3	24
	Middle	Tractor	123.7	39.5	8
		Middle	106.5	43.7	8
		Wagon	74.6	34.5	8
		Total	101.6	43.0	24
	High	Tractor	184.1	15.1	8
		Middle	163.9	134.4	8
		Wagon	116.8	11.2	8
		Total	154.9	80.2	24
	Total	Tractor	114.4	67.9	24
		Middle	124.9	84.9	24
		Wagon	74.4	45.3	24
		Total	104.6	70.5	72

sensor appeared consistent in comparison to the other sensor categories (except at the high setting), a human presence sensor with a possible window of performance of 74.5 cm is not acceptable for a safety system intended to protect the operator's life. Also the CI/PI calculations for the optimum height configuration for the PIR sensor indicated that its prediction interval included a "negative" distance, meaning that there is a chance that this sensor would not detect the person until after they came in contact with the PTO hazard.

Table 3 (con't). Detection distances and standard deviations for each sensor, height, and approach configuration.

Sensor	Sensor Height	Approach Angle	Mean (cm)	Std. Dev. (cm)	N
Radar	Low	Tractor	149.2	17.0	8
		Middle	157.1	17.9	8
		Wagon	144.5	8.8	8
		Total	150.3	15.4	24
	Middle	Tractor	186.5	50.8	8
		Middle	167.0	12.9	8
		Wagon	145.8	6.0	8
		Total	166.4	33.7	24
	High	Tractor	118.6	23.2	8
		Middle	96.8	37.9	8
		Wagon	85.9	20.4	8
		Total	100.4	30.3	24
	Total	Tractor	151.4	42.9	24
		Middle	140.3	39.9	24
		Wagon	125.4	31.2	24
		Total	139.0	39.3	72

SAFETY SYSTEM

The prototype safety shut-off system was created and incorporated onto the John Deere 6400 tractor. This system disengaged the PTO, sounded a horn, and caused a strobe light to flash, providing audible and visual notification that the system was tripped. Preliminary testing of the safety system was done with and without a trailed implement to evaluate the system's performance with an implement attached. These tests, while not recorded or analyzed, demonstrated that the system was a viable option and worth further research.

CONCLUSIONS

A total of 288 walk tests were conducted to evaluate the performance of four sensor technologies: radar, radar/passive infrared, passive infrared, and microwave/passive infrared. Of these technologies, radar/passive infrared appeared to be the best sensor technology for detecting persons who approach the hazard area based on more consistent performance over the full range of mounting heights while also being able to detect a person BEFORE they entered the hazard zone. The radar sensor actually performed with the lowest standard deviation of all sensors when mounted in a low position, but the radar/PIR sensor more closely matched the detection distance desired for the hazard zone with this particular tractor-implement combination. Also, the fact that the radar/PIR sensor's detection area was not as affected by mounting height as compared to the radar sensor, provides greater flexibility in sensor placement, especially when high placement is desirable. In addition, previous work by Shutske (2001) suggested that dual sensing technologies incorporated into a single sensing unit (such as the radar/PIR) was desirable given the concerns related to false alarms (if two different technologies must "see" the approaching person before the sensor goes into an alarm state). Test results also demonstrate that the angle at which the sensors are approached had little effect on sensor performance (for all sensor technologies tested) as compared to the height at which the sensor was mounted.

Additionally, as part of this work, a low-cost prototype automatic shut-off system was designed, constructed, and demonstrated. The prototype design showed that it is possible to tie together a human presence sensor with a shut-off circuit to disengage the PTO when a person enters into the hazard area.

This work does not immediately suggest that human presence sensors and sensor-based shut off and control systems are the single answer to protect people against rotating agricultural machinery hazards. The real value of this work is that we have advanced the testing methods and analysis protocols, which hopefully will advance future design research with the ultimate goal of developing a robust, reliable, fail-safe sensor-based human presence detection and component shut-off system in the future.

FUTURE RESEARCH NEEDS

Next, suggested topics for future research are outlined. It should be stressed that since the sensor technologies tested within this work will continue to evolve and become more sophisticated and less costly, future work should incorporate new/improved sensors including perhaps new combinations of multiple-technology units. Specific research questions include:

What is the best and most consistent performing combination of multiple-technology sensors? Radar appears to have promise because both the radar-alone and radar/PIR sensors performed well. Combining sensor technologies appears to have benefits based consistent performance over a range of mounting locations, and their ability to limit false alarms (particularly if the unit's control systems circuit require that BOTH technologies detect before the unit goes into a detect condition). If multiple technology sensors are not the best answer, possibly an array of radar sensors that "watch" the hazard area at all heights would help overcome the deficiencies of the single radar unit that is mounted high, perhaps missing people who walk in under its coverage pattern.

Further development work is necessary to determine the performance of a sensor system over a range of environmental conditions found in the agricultural workplace and how performance changes over the useful life of a sensor system. These tests and most others cited in the literature are often performed in relatively "ideal" settings and do not account for changes or degradation in performance over time.

While the shut-off system developed in this work successfully disengaged the PTO, we must understand how any type of sensor-based system might be used in real-world conditions and whether operator dependence on the system might change operator behavior. For example, an operator with two tractors that has one equipped with a sensor system and one without, might become dependent on the safety system when operating the tractor with the system and increase his risk level when operating the tractor without a system. This is but one example of additional human factors research needed if such a system is ever to be brought into full-scale commercial production.

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