Guard interlocking for self-propelled harvesting machinery

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Guard interlocking for self-propelled harvesting machinery

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Recent agricultural accident statistics are reviewed with reference to self-propelled harvesting machinery and particularly combine harvester grain storage & discharge systems, to enable identification and assessment of potential risk(s). The feasibility of utilising guard interlocking safety systems to prevent combine grain tank (and other) related accidents is investigated, and alternative designs of guard interlocking systems considered. A guard interlocking system design, based upon human presence detection sensors, was considered most suitable for the application and was subsequently installed upon a representative modern combine harvester. The prototype system was demonstrated and subjected to limited field evaluation, during which it returned promising performance. Whilst requiring further commercial development and field testing, the investigation has demonstrated the potential feasibility and benefits of such a safety system in this application.

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EXECUTIVE SUMMARY

This report describes research undertaken relating to the investigation and development of a prototype guard interlocking system suitable for use on self-propelled agricultural machinery, with particular emphasis upon improving combine harvester grain tank safety.

Recent farm accident information is reviewed and suggests that combine grain tank discharge and levelling augers are a significant cause of operator injury, but such injuries result almost entirely from intentional, unsafe entry into the grain tank. A review of combine harvesters currently available on the UK market indicates that virtually all modern combine designs incorporate folding grain tank covers which are opened during normal operation, often to form extension sides in order to increase tank capacity. Grain tank filling systems have developed to the extent where levelling augers are now rarely used, reducing the degree of risk, but grain tank designs now offer ready access from above, assuming it is physically possible for a person to reach the tank vicinity. This can be achieved on virtually all modern combines via the rear access ladder and thence the straw walker hood / engine bay. Knowledge of combine operation suggests that occasional circumstances will always arise when access to the tank area will be required, for removal of crop remnants, to assist discharge of bridged material, or for general maintenance purposes, some form of automatic discharge auger drive decoupling system appears desirable. The fact that modern combine grain tank discharge system engagement / disengagement is usually performed electronically, further encourages the consideration of some form of sensor-activated driveline disconnection system.

In the opinion of the authors, the nature of the grain tank access route and its permanent location, make the problem highly suited to the application of a safety interlocking system, incorporating one (or more) human presence detection (HPD) sensors. A review of HPD technology indicates that HPD sensors have developed substantially in the last 5 years, and now a wide range of robust units are readily available, utilising a range of sensing technologies. Capacitive and Combination Passive Infrared (PIR) / Microwave sensors were deemed most suitable for an on-combine application. Laboratory and field evaluation of sensors utilising these technologies were undertaken, during which both sensor types operated effectively in a (limited) range of typical combine operating conditions. The PIR / microwave sensor is both cheap (£45) and readily available off-the-shelf. It performed well throughout the investigation, but long-term robustness / reliability may be an issue. The capacitive sensor, whilst performing relatively well, has a shorter sensing range and could benefit from further development. However, its ability to utilise part of the combine structure as its sensing element, lends itself to incorporation within the combine at the time of manufacture.

It is therefore considered that human presence detection systems could be easily incorporated into an interlocked combine grain tank discharge auger disengagement system. A well-engineered system is likely to be of relatively low cost and a definite safety feature, whilst not restricting normal machine use. However, the scope for system evaluation within this investigation was undoubtedly restricted and any system would require further commercial infield development and evaluation. Additionally, the question of whether this approach to ensuring operator safety is adequate in isolation, was not addressed.
1. INTRODUCTION

Despite the increasing levels of comfort and hazard protection afforded to operators of modern self-propelled agricultural machinery, due to developments in cab and general vehicle design (see Figure 1), self-propelled harvesting machinery remains a major source of potential danger. In 1988 Chestney\(^1\) reviewed the frequency and specific nature of power driven machinery-related accidents: he also considered possible solutions to reduce or eliminate their occurrence. He found (from the farm accident data provided by the HSE at that time) that:-

- four machine types (potato harvesters, combines, forage harvesters & balers) accounted for 65% of guarding-related incidents: combines represented 16%, second only to potato harvesters (25%);
- many accidents resulted from the operator failing to disconnect drive to the machine before attempting to clear blockages or make adjustments;
- grain tank discharge (and/or levelling) augers were the greatest single cause of combine-related injuries (47%).

As combine harvester design has not changed substantially since 1988, grain tank discharge and levelling augers may remain a significant cause of operator injury today. Dwyer and Sanders\(^2\) concluded that the following range of generic options exist to improve the safety of power-driven agricultural machinery:-

a) improve the guarding integrity in the hazard area;
b) employ a system to automatically decouple the system drive when a person enters the hazard envelope;
c) modify design of the hazard area to reduce or eliminate the need for human entry.

With these options in mind, the objectives of this investigation were:-

a) To review recent agricultural accident statistics, with particular reference to self-propelled harvesting machinery (especially combine grain storage & discharge systems), to enable identification and assessment of potential risk(s);
b) To investigate the feasibility of guard interlocking systems (and/or alternative safety system(s)) to prevent combine grain tank (and other) related accidents;
c) To propose a functional specification and corresponding alternative designs of guard interlocking systems, and/or alternative solutions, to prevent combine grain tank-related incidents;
d) To construct and install the preferred guard interlocking system design on a representative modern combine harvester;
e) To demonstrate and evaluate the prototype system in the laboratory and the field.
2. SELF-PROPELLED HARVESTER OPERATOR HAZARDS

2.1 ACCIDENT STATISTICS

Given the past identification of combine harvesters, and specifically their grain tank discharge and levelling systems, as major causes of operator injury, it was important to determine whether, despite possible improvements in machine design, these machine components remain a potential hazard today. This is particularly relevant given the ongoing revision of ISO 4254-7:1995 regarding combine harvester, forage and cotton harvester safety, by ISO TC 23/SC 7/WG 3.

Combine harvester-related accident information supplied to ISO TC 23/SC 7/WG 3 by the German health and safety organisation for agriculture (Bundesverband der Landwirtschaftlichen Berufsgenossenschaften) showed that, over an unspecified period, 32 accidents had occurred. Of these 7 incidents (22%) concerned grain tank discharge or levelling augers, of which 2 (29%) resulted in limb amputations and a further 2 incidents (29%) caused fatalities.

Combine harvester-related accident statistics supplied to ISO TC 23/SC 7/WG 3 by the UK Health & Safety Executive (HSE), for the period 1986-1999 showed comparable trends, grain tank discharge or levelling augers being responsible for 25% of the recorded injuries, 18% of these resulting in fatalities (see Table 1). Given the similarity between the German and British data, it appears reasonable to conclude that combine grain tank-related accidents remain a significant identifiable cause of agricultural injury and consequently safety systems which may potentially reduce incident occurrence are worthy of further investigation.

<table>
<thead>
<tr>
<th>Accident Cause</th>
<th>Fatalities</th>
<th>Major Injuries</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run Over</td>
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<td>5</td>
<td>9</td>
</tr>
<tr>
<td>Grain tank augers</td>
<td>4</td>
<td>18</td>
<td>22</td>
</tr>
<tr>
<td>Overturns</td>
<td>2</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
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<tr>
<td>Falls</td>
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<tr>
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</tr>
<tr>
<td>Header</td>
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<td>11</td>
</tr>
<tr>
<td>Header fell from trailer</td>
<td>-</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Straw chopper</td>
<td>-</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>13</strong></td>
<td><strong>76</strong></td>
<td><strong>89</strong></td>
</tr>
</tbody>
</table>
2.2 COMBINE HARVESTER GRAIN TANK SAFETY

2.2.1 Sources of risk

Combine operators tend to enter the vicinity of the grain tank area for the following reasons:-

a) to open / close the grain tank lid (if manually-operated) when starting / finishing work;
b) to obtain samples of grain to verify the correct operation of the threshing / separation / cleaning systems and check crop quality / moisture content;
c) to assist / encourage discharge of poor-flowing / bridged material;
d) to effect removal of crop remnants (upon changing crops and/or varieties);
e) to undertake system maintenance.

Depending upon specific machine design, these actions could be undertaken with the grain tank unloading and/or levelling augers in motion, and represent extremely dangerous practice. However, steps have been taken in combine design to reduce operator safety risks in this specific machine area.

2.2.2 Grain tank covers

Virtually without exception, all new combines currently on sale in the EU embody some form of grain tank cover, typically in the form of a hinged, sheet steel assembly which folds upwards and/or opens for machine operation. In the case of machines sold in the UK which originate from major manufacturers (Claas, New Holland, John Deere, AGCO), the tank cover completely encloses the (empty / partially empty) grain tank when the machine is not in operation (see Figures 2 & 3). However, prior to machine operation, it is either essential or very common practice, to open the grain tank cover, either to increase tank capacity or simply to reduce dust levels in the vicinity and aid inspection of the tank contents. In fact virtually all modern combine manufacturers utilise the grain tank cover to form part of a tank vertical extension assembly, thereby increasing overall grain tank capacity. In such instances the top of the tank is either partially enclosed (Figure 4) or totally open (Figures 5 & 6), potentially permitting ready access via the rear of the machine (Figure 7). Combine grain tank covers are either opened manually, by virtue of a lever system accessible from small steps placed immediately outside the cab door, or more commonly electric or hydraulic actuators fitted within the tank enable remote operation of the covers from within the cab. In such instances, a warning system alerts the operator if the threshing mechanism is engaged with the tank covers closed.

Consequently, increases in combine size / capacity and the consequent need for increased grain tank capacity during operation, whilst still providing minimal overall height for machine transport and storage, have resulted in the almost universal use of grain tank covers as tank vertical extension sides, potentially enabling ready human access from above. Such implementations are made possible by the very common use of centrally-mounted fountain / bubble-type grain tank filling augers in modern combine grain tank designs (see Figure 8), which enable the entire tank volume plus extension to be filled with grain, whilst alleviating the need for additional levelling augers. This contributes substantially to machine safety as, during normal field operation (not during unloading), only the central filling auger will be in motion and, depending upon tank grain level, this may well be submerged. During (static) unloading it is not essential to have the threshing mechanism, and hence the tank filling auger, in operation.
Figure 1  Modern combine harvester at work

Figure 2  New Holland TX series combine grain tank cover (closed)
Figure 3  Massey Ferguson MF32 combine grain tank cover (closed)

Figure 4  Claas Lexion 440 combine grain tank cover (operating position)
Figure 5  New Holland TX series combine grain tank cover (operating position)

Figure 6  Claas Lexion 480 combine grain tank cover (operating position)
Figure 7  Grain tank access via combine rear (New Holland TX series)

Figure 8  Grain tank filling auger (MF32)
2.2.3 Grain sampling

During normal combine operation it is often necessary to obtain grain samples from the grain tank in order to verify correct operation of the threshing / separation / cleaning systems and check crop quality / moisture content. Whilst in the past this may have been achieved by simply taking a handful of grain from the top of the tank, often during machine operation; the presence of tank filling and especially levelling augers and associated drivelines makes this an extremely dangerous course of action. Fortunately the increasing size and/or height of grain tanks has virtually made such an action a physical impossibility on modern machine, especially if the tank is partially empty. Combine manufacturers have also responded to the problem by the provision of grain sampling doors / hatches in the vicinity of the operator platform, which enable a small sample to be obtained without entering the tank.

2.2.4 Grain tank unloading and cleaning

In the case of any machine human hazard, where the hazard is an essential part of the machine's operation, it is undoubtedly desirable to modify the design of the hazard area to reduce or eliminate the need for human entry. Grain tanks must be filled and subsequently discharged, and given the system performance constraints its is highly likely that mechanical conveying systems will remain the preferred solution and consequently remain a potential hazard. That said, there is absolutely no reason why an operator should need to enter a combine grain tank during normal field operation, unless a problem has occurred, in which case drive to the hazard area should be disconnected prior to entry. Combine grain tank discharge systems are designed to operate reliably in a wide range of crop conditions and they usually meet this requirement. However there will always be infrequent instances when the tank fails to discharge properly, due either to the type of crop (e.g. herbage seed) or crop physical properties on a particular occasion (e.g. excessive moisture content). In such instances the grain tank contents may "bridge" and fail to flow freely to the discharge auger in base of the tank. Anti-bridging devices are available to assist the discharge of difficult crops and serve to reduce the frequency of the risk, but do not necessarily eliminate it. Also, the majority are offered as machine optional extras, requiring prior decision on the part of the potential purchaser. Combine grain tanks could potentially be designed to reduce the likelihood of bridging, but given the infrequency of the problem and conflicts with tank capacity and machine packaging, the priority for redesign is suspected to be low. In any case, if a field situation occurs where a grain tank fails to discharge adequately, it is highly likely that human physical intervention will result. In such instances it is essential to ensure that the drive to the hazard area is decoupled prior to human entry, if necessary by automatic means.

As mentioned earlier (see Section 2.2.2) the widespread elimination of levelling augers from combine grain tanks has served to reduce the number of individual hazards in the area. Grain discharge is usually effected by one high-capacity transverse auger mounted in the base of the tank, feeding a vertical "turret" auger at one side, linked to a hydraulically-pivoting external (main discharge) auger. A sloping tank floor is usually the sole means of ensuring that grain moves to the transverse auger, although some older designs utilise additional feeder augers. Whilst effective and convenient, there remains a requirement for human entry into the tank in order to effect removal of crop remnants, particularly when moving between crops or seed varieties. This particular issue could be addressed by machine design modifications, either to enable tank cleaning to be effected from external points, or to incorporate a simple air-blast assistance system as commonly used on small plot combines. However, in any instance, the need for drive disconnection prior to tank entry (if unavoidable) is paramount.
3. COMBINE GRAIN TANK INTERLOCKING

3.1 SYSTEM FEASIBILITY

A recent review of guard interlocking systems for PTO-driven agricultural machinery (Semple & Scarlett) concluded that generic interlocking systems may have a range of operational objectives, including:

a) prevention of guard opening / removal whilst the machine is driven and/or in motion;
b) automatic disengagement of system drive when a person enters the hazard area;
c) prevention of driveline engagement whilst guards remain open and/or persons remain in the hazard area.

The potential advantages of guard interlocking, in terms of affording operator protection from moving components within any defined danger zone upon a given machine, are significant, assuming that such a system can be readily and economically incorporated into agricultural harvesting machinery. However the harshness of an agricultural operating environment i.e. dust, vibration, moisture and temperature variations, should not be underestimated.

Chestney (1988a) highlighted the benefits of such a system and proposed a guard interlocking system design for a combine. This system, which included interlocked protection of all main panel guards, grain tank & discharge auger access, and straw walker access, was subsequently implemented upon a machine and evaluated during the course of a harvesting season (Chestney (1988b)). Whilst largely successful, implementation of the (electronic-based) system was hampered to an extent by the lack of electronic communication and control hardware on the (mid-1980's) target vehicle. This necessitated retro-fitting of expensive additional items, some of which did not entirely meet the system requirements.

However since that time, the development and utilisation of electronic communication and control technology on agricultural vehicles indicates that future embodiments of combine guard interlocking systems could implemented with much greater ease and at lower cost. Whilst most recently launched combines utilise digital electronic communication systems (e.g. CAN-Bus, etc), electrical engagement / disengagement of the grain tank discharge system has in fact been present upon many combines for the last decade utilising in-cab switches, automotive relays and either electro-hydraulically tensioned drive belts or electromagnetic clutches for engagement of the discharge auger mechanical driveline. Consequently, it is a relatively simple prospect to incorporate additional safety switches and/or sensors in the discharge auger control circuit, effectively creating a form of guard interlocking system. Such an example is present upon the Claas Medion combine range, where access to the rear of the grain tank (via the straw walker hood) necessitates the use of a spring-loaded intermediate step. Movement of the step is detected by an in-built sensor, which triggers the tank discharge auger engagement relay, automatically disengaging the discharge system and preventing re-engagement unless the ignition switch (and engine) is turned off and on once again. This system could be defeated by two dedicated individuals (one in the cab and one above the triggered step), but such intentional actions can rarely be completely prevented. A similar safety switch is believed to be incorporated in the rear access ladder assembly of the recently-launched New Holland CX series combines.
3.2 SYSTEM FUNCTIONALITY

Guard interlocking systems, by definition, normally embody some form of physical guard to prevent access to the hazard area. However, in this application the hazard area (grain tank and associated augers) is frequently not enclosed during normal operation (with some notable exceptions, e.g. Claas Lexion 440 (Figure 4)) and is readily accessible, usually from the rear of the machine (see Figure 7). Combined with the fact that, in the case of current designs, it is necessary to permit human access into the grain tank for maintenance and cleaning purposes, the implementation of conventional physical guarding seems a challenging prospect. Consequently, without the option of preventing human contact with the hazard, the preferred / remaining option is to temporarily eliminate the hazard upon the presence of a person in the hazard envelope.

Given the sheer size of modern combine harvesters, and the size and location of the grain tank, we are fortunate that potential human access routes are limited to the extent that, without additional ladders, etc, ready access to the grain tank area can only be effected via the machine rear access ladder, thence over the straw walker hood / engine bay to the rear edge of the tank. This is a major benefit from a safety system viewpoint, providing as it does a number of locations at which the presence of a person may be detected.

In order to be effective, any combine human presence detection (HPD) system would have to:

- work reliably in a wide range of operational conditions;
- achieve disengagement of the hazard system before triggering target (person) could reach the hazard area;
- be relatively cheap and simple to implement.

As previously discussed (Section 2.2.2), modern combine grain tanks usually contain two major rotating hazards; the central filling auger and the base-mounted transverse discharge auger. Only the upper end of the tank filling auger is unguarded (see Figure 8), but as this component only rotates when the threshing mechanism is engaged, it need not be in motion during (static) tank discharge. If unloading is performed whilst the combine is in motion / work, the tank filling auger would be in operation, but it would be extremely unlikely for a person to be, or indeed need to be, in the vicinity of the grain tank. Whilst guarded to a degree from above by cover plates (limited due to conflict with its method of operation), the transverse discharge auger represents a greater potential hazard. Therefore any combine harvester grain tank guard interlocking system must effect disengagement of the tank discharge system driveline before an individual enters the hazard envelope.

Consequently, at this point the investigation it was decided to concentrate efforts upon development of a suitable human presence detection system for an operational combine harvester.
4. HUMAN PRESENCE DETECTION SYSTEMS

4.1 SENSING TECHNOLOGIES

The following generic sensing technologies may be successfully applied to human presence detection:

- Physical Contact
- Light Beams
- Infrared Emission
- Radar (microwave)
- Capacitive

Physical contact sensing involves touching or breaking a physical component, for instance triggering a switch or stepping on a pressure pad or mat. A switch or switches could be incorporated as part of a mechanical system (e.g. Claas Medion access step): alternatively non-contact (proximity) switches could be used (e.g. New Holland CX rear access ladder). All systems depend upon the electrical reliability of the switch(es) (usually very good), but suffer from the fact that installations can normally be detected and their mode of operation easily appreciated by the machine operator. This can encourage intentional bypassing. Agricultural operating environments do not usually present a problem to well-engineered installations.

Light beam systems typically comprise a source which emits one (or more) narrow, parallel light beams, which are subsequently detected by a corresponding unit placed opposite the emitter. If any of the beams should fail to reach the detector, for instance due to a physical object blocking it, the overall detection system is triggered. Such systems are frequently used in well-defined, stationary applications, but they are less well suited to applications where significant dust or vibration may be present, dust potentially interrupting the beams whilst vibration may cause emitter / detector alignment difficulties. Once again, light beams are a highly 'visible' detection system and therefore encourage intentional avoidance, but their practical field of operation can be much wider than physical contact devices. Infrared light may be substituted for visible light, and such systems are believed to be more suitable for harsh, external operating environments.

Passive infrared emission (PIR) sensing is commonly used in domestic intruder detection systems and for automatic light operation. An electronic detector monitors infrared radiation within a number of sensing zones in the vicinity of the sensor unit (see Figure 9), the zones having been created by a Fresnel lens incorporated in the sensor housing (see Figure 10). The background radiation level is monitored continuously, but should an infrared radiation (heat) source move across one (or more) sensing zones, the unit will trigger, having sensed both a change in heat and/or object motion. This sensing technology has not been widely applied to mobile equipment, potentially being prone to false triggering in unstructured environments. However, its low cost, ready availability and relatively good environmental performance encourage its consideration.
Microwave radar sensors transmit microwave pulses and monitor the reflected signal: should an object move in the sensing zone, the reflected energy level changes and the sensor is triggered. The Doppler shift principle may also be utilised, whereby the change in frequency of the reflected microwave signal indicates object motion. Whilst Doppler shift sensors are commonly used for true forward speed measurement on agricultural tractors, reflected energy level sensing is more commonly used by human presence detection sensors which are freely available on the domestic market. Potential disadvantages include susceptibility to any
(sufficiently large) moving objects within the sensing range, possible susceptibility to vibration, and sensitivity to RF emissions from other sources.

Capacitive sensors operate on a 'proximity' basis by monitoring the current or charge flow into a defined capacitive system, typically comprising a metal sensing plate mounted a small distance away and electrically isolated from a base object e.g. a steel structure. Should a human body approach the sensing plate, the system capacitance and the resultant charge flow will change. Sensing range is dependent upon the sensitivity with which system capacitance changes may be detected. An inherent drawback is that the presence of any biological object containing a high proportion of water (e.g. green vegetative material) will potentially trigger the sensor.

4.2 PREVIOUS WORK

A significant amount of previous research regarding the use of human presence detection systems in agriculture has been undertaken, the majority in the USA. However, in many instances, developments in sensor technology and availability have provided solutions to a number of previously-encountered problems.

Murphy and Morrow (1996) undertook a broad review and analysis of commercially available and prototype human presence detection systems. They concluded that (at that time) few sensing systems showed sufficient promise for use on agricultural equipment to reduce human risks, given the constraints and limitations identified by industry. However, the most promising sensing systems were those which utilised either capacitive or microwave radar technologies.

Buck and Aherin (1991) developed a prototype capacitive sensor for human presence detection in the vicinity of agricultural equipment, and achieved sensing ranges of up to 20 cm. The system was insensitive to small objects and dry organic matter, and could function both when wet or covered in mud. However, sensitivity to green vegetation was a drawback.

Since 1994, a team of researchers at the University of Minnesota, USA, led by John Shutkske, have been undertaking a programme of human presence sensor evaluation in agricultural machine operating environments. The programme has concentrated upon determining the ability of commercially-available sensors to detect a worker approaching the hazard zone between a tractor and trailed, PTO-driven implement. Modern sensors which utilise two complimentary sensing technologies linked by electronic logic (combination Doppler shift microwave and passive infrared (PIR), or combination Doppler shift and reflected power microwave) have demonstrated very promising results. Sensor siting and PIR sensor beam angle were considered to be important issues which affect overall system performance.
5. COMBINE HARVESTER DEMONSTRATION SYSTEM

5.1 SYSTEM INSTALLATION

Upon consideration of the probable on-combine sensor operating environment (e.g. heat, dust, hot moving grain, & vibration), review of previous research, and survey of readily-available (economically-feasible) sensor technologies, two sensor types were selected for installation upon a Claas Dominator 108 SL combine (see Figure 11) and subsequent laboratory and in-field performance evaluation upon. They were:

a) Combined passive infrared (PIR) and microwave;
b) Capacitive.

Figure 11  Claas Dominator 108 SL (target combine used in the investigation)

The PIR / Microwave sensor was a commercially-available unit (C&K Systems Dual Tec DT-640STC), usually sold for domestic intruder detection purposes. Whilst usually having a sensing range extending to approximately 12 metres (see Figure 9), the sensing zone span was reduced to approximately 3 metres for this application, by attaching a rudimentary, parallel-sided, open-ended box assembly to the Fresnel lens section of the sensor body. This effectively narrowed the sensing zone to suit the combine installation (see Figure 12). The principles of operation of PIR and microwave sensors have already been discussed (see Section 4.1), but combination sensors of this type utilise the best characteristics of both sensing technologies, by linking their outputs via Boolean logic. Three logic options are available within this particular sensor, each requiring the PIR and microwave sensing elements to be triggered two or more times within specified time intervals of each other, before the main (external) sensor output is enabled. One option even specifies the polarity of subsequent PIR trigger instances (adjacent PIR sensing zones generate responses of different
polarity (see Figure 9). These alternative settings effectively reduce the (combined) sensor unit's susceptibility to false triggers (e.g. passing domestic animals), whilst still permitting reliable human presence detection, enabling overall unit sensitivity to be refined to suit the chosen application.

Figure 12  Capacitive (right) and PIR / microwave (left) sensors installed on the target combine

The capacitive sensor was partially developed in-house at Silsoe Research Institute, utilising a recently available capacitance sensing circuit (Quantum Research Group Qprox QT9701B2 charge-transfer capacitance sensor integrated circuit). Essentially the system comprises a high-performance, microprocessor-based signal processing circuit, which when connected to a suitable metal plate / object, creates a capacitive proximity sensing system. Operating on the charge transfer principle, the microprocessor-based circuit controls and records charge transfer to the sensing plate, intelligently monitoring the quantity of charge required to reach a threshold level, which is dependent upon system capacitance. The sensing circuit automatically compensates for background capacitance during operation, but the approach of a human body causes a sufficient change in system capacitance to trigger the sensor. A number of alternative sensing plates were evaluated (see Figure 13), as plate size was deemed likely to affect sensor performance (sensitivity / range).

Both sensors were mounted on the rear right-hand side of the combine grain tank (Figure 12), at the top of the rear access platform (Figure 14). This was deemed to be the only feasible access route to the grain tank; detection of human presence upon the platform at the top of the rear access ladder, and immunity to false triggering, being the criteria for successful sensor operation. Both sensors were linked to an in-cab operator alarm / display unit (see Figures 15 & 16), which indicated both when a sensor had been triggered and its identity. It was decided
not to link the sensors to the combine tank discharge system control circuit during the investigation (although this could have been accomplished easily), because sensor system performance was deemed to be the main evaluation criteria in this instance.

**Figure 13** Capacitive sensor alternative sensing plates

**Figure 14** Rear access route of the Claas Dominator 108 SL combine
Figure 15  Schematic circuit of sensor system installation

Figure 16  In-cab operator alarm / display unit
5.2 SYSTEM EVALUATION

Evaluation of the system was intentionally restricted, especially when viewed from a commercial standpoint, but the trials performed served to prove the suitability of both sensing systems for further commercial development and evaluation. Laboratory evaluation involved the repeated approach of a 1.8 m tall, 77 kg man to the sensor installation, via the combine rear access ladder and platform (see Figure 14). In each instance the sensor(s) were deemed to have operated successfully, if triggering occurred before it was physically possible to mount the straw walker hood.

In all instances the PIR / microwave sensor triggered once the man had either reached the ladder top, or had just stepped onto the rear access platform, the latter being approx. 1 m long. This was considered entirely adequate performance. The capacitive sensor exhibited a smaller sensing range than the PIR / microwave unit, this being dependent upon sensing plate size and (possibly) air temperature and humidity. Referring to Figure 13, sensing plate (a) regularly achieved a sensing distance of approximately 330 mm, whereas sensing plate (b) achieved 370 mm and sensing plate (c) achieved 490 mm in the same conditions, using identical methods of evaluation. Such change in system performance is predictable, and a 350 - 400 mm sensing range is probably adequate for a commercial implementation, given the proposed location of the sensor relative to the hazard envelope. However, subsequent field evaluation of sensing plate (c) did indicate a greater susceptibility to false triggers than either plates (a) or (b).

Likely system evaluation variables were deemed to be:-

- Size of the person;
- Route and speed of approach;
- Combine operational state:-
  - threshing mechanism engaged / disengaged;
  - straw chopper in operation / idle;
  - grain tank unloading mechanism engaged / disengaged;
  - grain level in tank prior to unloading;
  - vehicle stationary / in motion.
- Ambient temperature / lighting / humidity;
- Rainfall ?

False triggering sources were deemed likely to be:-

- Dust / crop material;
- Vibration - (threshing mechanism / straw chopper / unloading mechanism operation; surface rutting);
- Adjacent trees / hedges / telegraph poles.

Field evaluation was performed primarily by simply undertaking normal combine operation, both with the straw chopper engaged and disengaged, including unloading the grain tank whilst on-the-move (see Figure 17) and stationary (see Figure 18). During the evaluation approximately 21 hectares of wheat was harvested, comprising some 122 tonnes of grain, over a total operating period of 21 hours (4 separate fields). No false triggers occurred during normal harvesting (not unloading), but each tank unloading operation was evaluated separately, as it provided a major source of vibration to the sensor mountings.
Prior to each unloading operation (tank usually full), correct operation of each sensor was verified by a man approaching the installation via the defined route. Following successful verification, grain tank discharge was performed and any sensor triggers noted. Of a total of 13 static unloading operations and 11 performed on-the-move, no PIR/microwave false triggers were recorded and only 1 capacitive sensor false trigger occurred. However, these results were obtained with the smallest sensing plate (Figure 13(a)) fitted: use of plates (b) and (c), whilst increasing system sensitivity, resulted in a greater number of false triggers when unloading statically, approaching 50% of instances on one occasion. However, it is likely that such characteristics could be substantially reduced with further sensor development. During testing it was noted that false triggers (as provided by the larger capacitive sensing plates) were more prevalent during static unloading. This is thought to be due to the greater vibration of the grain tank and combine body during static unloading, possibly resulting from discharge auger engagement, compared to that experienced during discharge on-the-move, when combine forward motion and operation of the threshing mechanism appear to provide a stabilising and/or damping effect.

During the test programme both sensors were approached (with the combine static) a total of 37 times, during which neither unit failed to register human presence. Sensor response to adjacent objects (e.g. trees) was also determined (see Figure 19). The combine was reversed beside a large, leafy chestnut tree, to a point where the leaves brushed the grain tank side. During four separate passes the capacitive sensor triggered twice (50%), but the PIR/microwave unit was unaffected. On one other occasion during field operation, the capacitive sensor was triggered by parts of a hedge in close proximity to the sensor unit. Whilst this behaviour is to be expected of this sensing technology, one must question the need to unload a combine grain tank when very close to a tree or hedge.

![Figure 17](image-url)  
*Figure 17 Unloading the combine grain tank “on-the-move”*
Figure 18  Unloading combine grain tank whilst stationary

Figure 19  Testing sensor response in close proximity to trees / hedges
6. DISCUSSION

The farm accident information reviewed by this investigation suggests that combine grain tank discharge and levelling augers are a significant cause of operator injury, but such injuries result almost entirely from intentional, unsafe entry into the grain tank. Virtually all modern combine designs incorporate folding grain tank covers which are opened during normal operation, often to form extension sides in order to increase tank capacity. Grain tank filling systems have developed to the extent where levelling augers are now rarely used, reducing the degree of risk, but grain tank designs now offer ready access from above, assuming it is physically possible for a person to reach the tank vicinity. This can be achieved on virtually all modern combines via the rear access ladder and thence the straw walker hood / engine bay. Given that circumstances will always arise when access to the tank area will be required, for removal of crop remnants, to assist discharge of bridged material, or for general maintenance purposes, some form of automatic discharge auger drive decoupling system appears desirable. The fact that modern combine grain tank discharge system engagement / disengagement is usually performed electronically, further encourages the consideration of some form of sensor-activated driveline disconnection system.

The nature of the grain tank access route and its permanent location, make the problem highly suited to the application of a safety interlocking system, incorporating one (or more) human presence detection (HPD) sensors. HPD technology has developed substantially in the last 5 years, and now a wide range of robust sensors are readily available, utilising a range of sensing technologies. Capacitive and Combination Passive Infrared (PIR) / Microwave sensors were deemed most suitable for an on-combine application. Laboratory and field evaluation found that both sensor types operated effectively in a (limited) range of typical combine operating conditions. The PIR / microwave sensor is both cheap (£45) and readily available off-the-shelf. It performed well throughout the investigation, but long-term robustness / reliability may be an issue. The capacitive sensor, whilst performing relatively well, has a shorter sensing range and could benefit from further development. However, its ability to utilise part of the combine structure as its sensing element, lends itself to incorporation within the combine at the time of manufacture.

Human presence detection systems could therefore be easily incorporated into an interlocked combine grain tank discharge auger disengagement system. A well-engineered system is likely to be of relatively low cost and a definite safety feature, whilst not restricting normal machine use. However, the scope for system evaluation within this investigation was undoubtedly restricted and any system would require further commercial in-field development and evaluation. Additionally, the question of whether this approach to ensuring operator safety is adequate in isolation, was not addressed.
7. CONCLUSIONS

The objective of this investigation was to undertake research relating to, and development of, a prototype guard interlocking system suitable for use on self-propelled agricultural machinery; with particular consideration of combine harvester grain tanks. With this in mind, the following conclusions may be drawn:-

- Combine grain tank discharge and levelling augers are a significant cause of operator injury, but most accidents result from intentional entry into the grain tank hazard envelope;

- Virtually all modern grain tank designs incorporate folding covers, which open during machine operation to form tank extension sides, frequently enabling ready human access from above, via the straw walker hood / engine bay area;

- Use of centrally-mounted, bubble-type tank filling augers has largely eliminated the requirement for grain tank levelling augers, leaving the tank discharge auger system as the major source of risk;

- As intentional grain tank entry will continue to occur in practice, for removal of crop remnants, to assist discharge of bridged material, or for general maintenance purposes, an automatic method of tank discharge system drive decoupling would contribute to machine safety;

- Practical limitations regarding current combine design, grain tank position and human access routes encourage utilisation of a driveline interlocking system incorporating human presence detection (HPD) sensors;

- Capacitive and combination passive infrared (PIR) / microwave human presence detection technology was considered to be most suitable for this application. Limited laboratory and field evaluation indicated promising performance;

- The PIR / Microwave sensor used is cheap, readily available and gave reliable performance, but its long-term robustness / reliability requires further evaluation;

- The Capacitive sensor exhibited shorter sensing range and a greater propensity to false triggering, but it benefits from an ability to be installed as part of the machine structure and be refined to suit the target application. This sensor technology is therefore considered to be worthy of further investigation and/or development;

- An HPD-based interlocking system could be easily incorporated within modern combine grain tank discharge systems at relatively low cost, and contribute to operator safety. Whilst significant promise has been demonstrated, further commercial development and evaluation is undoubtedly required. Also, consideration of whether additional safety systems are required, in order to ensure adequate operator protection, may well be necessary.
8. REFERENCES


