Development of an automatically deployable roll over protective structure for agricultural tractors based on hydraulic power: prototype and first tests

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Abstract

An inadequate use of the deployable Roll Over Protection Structure (ROPS) in agricultural tractors contributes to fatalities in rollover events. To help to resolve this problem, an automatically deployable ROPS was designed, constructed and tested. The prototype, called HydraROPS, established two assistance levels for the elevation of the foldable ROPS. In the first level, the driver decides to change the ROPS' position and this change is made using the manual activation on the board. In the second level, an automatic change to the operative position occurs in situations of impending rollover, without the intervention of the driver. In this level, it automatically sends a phone message with the GPS location to contact emergency response

personnel. The tractor's hydraulic power was used to move the protective structure. In order to increase the deployment speed of ROPS, a pressure accumulator was included in the hydraulic circuit. The deployment time of the ROPS without the pressure accumulator was 2.599 s and with the pressure accumulator 0.743 s. The results of the research show that the pressure accumulator assembled in the hydraulic circuit reduced the deployment time of ROPS by 71%; and that the electronic control system can correctly predict overturn. HydraROPS has the advantage compared to other automatic deployment devices of protective structures that can be installed on tractors equipped with a certified rollover protective structure. The installation in marketable tractor models does not modify the protection structure; therefore a new certification of the protection structure is not necessary.

Keywords: Tractor safety; Overturn; ROPS; Injury; Emergency notification.

1. Introduction

Tractor overturns are the leading cause of fatalities in the agricultural industry. In USA, nearly 50% of tractor fatalities come from tractor overturns (HOSTA, 2004). In Australia, over the 2004-07 period, 65 fatalities occurred due to working with tractors, 17 of the deaths (26%) were due to tractor rollover (SWA, 2011). In the EU, a survey carried out by the European Commission of EU member states revealed that 40% of serious injuries and deaths during tractor overturns occurred when a foldable ROPS was not deployed into its protective position (Hoy, 2009). In Spain, between 2004 and 2008 the main cause of death in the agriculture sector was the tractor overturning (70%) (Arana et al., 2010). In the Region of Murcia (Spain), over the 2005-2012 period, in 11 of the 44 accidents with tractors, the Roll Over Protective Structure (ROPS) was down at the time when the accident occurred, and this contributed to fatal accidents (Martin-Gorriz et al., 2012). Narrow-track tractors and standard tractors equipped with foldable ROPS are permitted in orchards and vineyards with lowered ROPS. However, due to their complicated ergonomics and the difficulty of handling by the operators, the ROPS tend to remain folded at all times. The consequence is clear; a misuse of the ROPS makes it highly inefficient as a rollover protection system.

A large number of recent publications are related to applying new technologies and design solutions to promote the automatic deployment of protective structures. Powers et al. (2001) developed an automatically deployable rear-mounted ROPS. It consisted of two subsystems, the first one is a retractable ROPS, which is normally latched in its lowered position for day-to-day use, and the second is a sensor that monitors the operating angle of the tractor. In the event of an overturn, the sensor detects the angle and the retracted ROPS is deployed automatically and locked in the fully upright position before ground contact. This deployable ROPS requires no action to be lifted because it is compressing two springs, located into the fixed part of the ROPS that lift it when two pins that hold the structure in the retracted configuration are simultaneously disengaged by solenoids. Silleli et al. (2007) introduced an additional system for narrow-track orchard and vineyard tractors, developing an automatically deployable telescopic structure which increases the top width of a front-mounted roll bar. The system increased the protection efficiency of the ROPS for the tractor operators and at the same time reduced the overhead clearance required by these machines, to improve potential usage in orchard and vineyard conditions. Ballesteros et al. (2013, 2015) developed and tested an automatically deployable front-mounted ROPS for narrow tractors, using airbag inflators, able to simultaneously increase the height and the upper width of the ROPS. The double change of the ROPS geometry reduces the continuous rolling risk, increases the safety zone in a lateral direction, and allows a reduction in the ROPS height, the bending moments at critical sections, and the ROPS beams sections.

Other researchers have focused on developing systems capable of informing the tractor operator of the stability of the tractor at all times. Nichol et al. (2005) proposed a device using low-cost sensors and microcomputers to inform the operator of potential tractor instability. DTAEBT (2015) developed an electronic device to monitor tractor stability on sloping ground. Its purpose is to gradually warn the operator as the instability and rollover risk increase. The device called IncliSafe can be bought as an aftermarket add-on for a variety of tractor models. Liu and Koc (2013, 2015) developed a smartphone application to transmit the accelerometer and gyroscope signals from a smartphone's built-in sensors to a computer over a wifi network. The application, called SafeDriving, proved how a mobile phone can be used to collect data for the stability assessment of a tractor during operation. These systems try to teach the operator what the risk situations are and what they can do to avoid them.

The present research sought to develop and test a new automatic system to deploy the ROPS on tractors using hydraulic power; hence this ROPS has been named 'Hydraulic deployment ROPS' (HydraROPS). Two possible options for deploying the ROPS have been considered: (1) the system informs the tractor driver that the stability of the tractor has reached dangerous levels. In the situation above, the driver will be able to use the mechanism to raise the rollover protective bar from the driving seat; and (2) the system automatically deploys the ROPS when the tractor is near to the point of rollover. In this option, it automatically sends a phone message with the GPS location to contact emergency response personnel. This could result in a quicker and more efficient response by emergency personnel, which may in turn save lives or improve the recovery time for non-fatally injured victims.

2. Materials and methods

2.1. Design requirement

HydraROPS is composed of two subsystems: (i) an electronic control subsystem, and (ii) a hydraulic subsystem to move the ROPS. The requirements for the electronic control subsystem were the following:

- It will be possible to change the ROPS position when the driver recognises a risk situation.
- Should an immediate rollover condition exists, the ROPS will deploy automatically without the intervention of the driver.
- Should a potential rollover condition exist, an audible signal will alert the driver.
- Immediately after a rollover situation, the system will send geographic coordinates of the tractor's location to the emergency call centre.
- The information related to the movement of the ROPS will be recorded. This data can prove critical in reconstructing the accident. When the ROPS is deployed (manual or automatic mode) time, pitch angle, roll angle and GPS coordinates are recorded. In automatic mode this is recorded plus GPS.

The requirements for the hydraulic subsystem were the following:

- The deployment time of the ROPS will be in time to stop the tractor from rolling onto the driver.
- The ROPS will remain deployed when the tractor is switched-off.

In addition, HydraROPS should be as economical as possible to promote its installation by farmers on their tractors with a front-mounted foldable ROPS.

The main advantages of the use of the hydraulic power of the tractor for the deployment of the ROPS are (1) It uses a type of power that exists in all the tractors, and as a part of the tractor circuit is used, this reduces the economic cost of the installation;(2) It can be operated as many times as necessary, (3) It takes up little space and does not interfere with other uses that the farmers give a tractor.

2.2. Control algorithm

Tractor overturns are related to various factors, such as a tractor's dimensions, the relative position of the centre of gravity, and dynamics, such as speed, turning radius and terrain. The stability of a tractor can be classified into static and dynamic stabilities. A stability index based on static stability is simple, thus it is more easily applied as the first step to automatic intervention in an engineering control. In this research, the mathematical model proposed by Liu and Ayers (1998) was used. The authors proposed the development of a stability index in a combination of pitch and roll (SI_{COM}). Their work showed that the stability indices indeed predicted instability at the times of overturn for both side and rear overturn. The details of this control algorithm can be found in Liu and Ayers (1998). The overall stability index value was calculated using the following equation (1):

$$SI_{COM} = \left[1 - \sqrt{\left(\frac{\theta^2}{\theta_{cri}^2} + \frac{\phi^2}{\phi_{cri}^2}\right)}\right] \text{x } 100 \qquad (1)$$

where θ and ϕ are the pitch angle and roll angle of the vehicle and θ_{cri} and ϕ_{cri} are the critical pitch angle and critical roll angle, at which lateral or longitudinal overturning is about to happen. The stability index (SI_{COM}) values range between 0 (least stable) and 100 (most stable). The algorithm for activating deployment of a safety system proposed by Liu and Ayers (1998) was the following criteria (2):

$$SI_{COM} \leq SI_{cri} = 0 \qquad (2)$$

2.3. Electronic control subsystem

The electronic control subsystem was designed for two modes of operation (Fig. 1): mode 1, voluntary operation by the tractor driver, and mode 2, automatic operation in the event of imminent roll over. The software uses the physical parameters of the tractor and the data from the sensors of the electronic subsystem to conduct the signal processing and implementation of the control algorithm. Two warning levels were defined. In the first level, when the stability index (SI_{COM}) value was below 40, an audible warning signal was switched on, and the second level, when the SI_{COM} value was below than 20, the ROPS was deployed.

[Figure 1. insert here].

The electronic control subsystem which acts on the hydraulic circuit was based on a microcontroller board with other components. Fig. 2 shows the system architecture of the HydraROPS prototype. The components that were used in the electronic control subsystem were the following:

1. **Microcontroller circuit.** An Arduino ATmega2560 microcontroller board was used that has a number of I/O ports suitable for the electronic components used. The assembly of the components was modular. The software was programmed in the C language. Fig. 3 shows the flowchart for the algorithm used by the microcontroller.
2. **Inertial measurement unit.** An inertial measurement unit (PMU6050) composed of an accelerometer and a gyroscope was used. This device senses static and dynamic accelerations and computes the angle at which the tractor is operating. A Kalman filter was used to filter the noise from the accelerometer and gyroscope sensors. The Kalman filter is a set of mathematical equations that provide an optimal means of estimating the state of a process so that the error is minimised. This filter is widely used in navigation and control systems.

3. **Communication module.** The communication module SIM908 was used to connect GSM network and receive GPS. This shield with a Quad-band GSM/GPRS engine works on frequencies EGSM 900MHz/DCS 1800MHz and GSM850 MHz/PCS 1900MHz. It also supports GPS technology for satellite navigation. The combination of both technologies allows goods, vehicles and people to be tracked seamlessly at any location and at any time with signal coverage. When the device operates automatically (mode 2) the GSM/GPRS module was activated and sends a short message (SMS) with the geographic coordinates of the tractor's location. This could result in a quicker and more efficient response by emergency personnel, which may save lives or improve the recovery time for non-fatally injured victims.
4. **Memory card.** The microSD memory card (Arduino microSD shield) was used to record the data. When HydraROPS was moved manually or automatically the following data were recorded in the memory card: time (hh:mm:ss), pitch angle (degrees), roll angle (degrees), geographic coordinates (longitude and latitude), position of the ROPS (horizontal or vertical position) and mode to switch-on the ROPS (mode 1 or 2).
5. **Relay module.** In the full-scale tractor the relay module was used to operate the hydraulic subsystem. The normally open contacts of the relay were connected to solenoid valves that, when ignited, deploy the hydraulic cylinders of the HydraROPS. Solid-state relays were used because they are more robust than electromechanical relays. In the scale model tractor a solenoid coil was used to deploy the ROPS.

These electronic components were placed inside a box panel with IP (International Protection) code 66. The box panel was located close to the steering wheel of the tractor to make it easily accessible for the tractor driver, because in mode 1 the ROPS is switched on by the driver.

[Figure 2. insert here].

[Figure 3. insert here].

2.4. Hydraulic subsystem

HydraROPS was designed to be mounted on a tractor with a front-mounted deployable ROPS. Fig. 4 shows the hydraulic circuit of HydraROPS. In order to make the prototype less expensive, the hydraulic power of the tractor was used to move the deployable ROPS (Carraro, X 260-3). Two hydraulic cylinders, (CHB 50/30 – 150, stroke length of 150 mm, bore diameter of 50 mm, piston rod diameter of 30 mm and maximum operating pressure of 20 MPa) one on each side of the ROPS, raised and lowered the structure. In a preliminary study, it should be noted that deployment time was evaluated in comparison to other power sources such as spring action technology (Powers et al., 2001) or airbag inflators technology (Ballesteros et al., 2013). In order to solve this problem, a bladder pressure accumulator was included in the hydraulic circuit for faster deployment of the ROPS. In addition, the pressure accumulator (volume of 1.5 L and pressure of 7 MPa, Hydro Leduc, Azerailles, France) allows a last activation of the ROPS even though the tractor engine has been switched off.

[Figure 4. insert here].

2.5. Economic assessment

Figure 5 shows hydraulic and electronic components of HydraROPS installed in a Case 2120V tractor with a certified protection structure. Figure 6 shows this tractor with ROPS in retracted position and in deployed position. The total cost to place the HydraROPS in this tractor was 2176 €. Hydraulic components were the highest item totalling 1016 € (47 %), followed by the electronic components at 522 € (24 %). The cost of the labour to assemble the electronic and hydraulic components was 636 € (29 %). The cost reported here was for a prototype device. The device is not yet marketable. This cost can no doubt be reduced with large scale quantities. In the not too distant future, we aim to sell HydraROPS as a kit for marketable tractor models with a front-mounted deployable ROPS.

[Figure 5. insert here].

[Figure 6. insert here].

3. Performance evaluation

3.1. Electronic device test in scale tractor

The evaluation of the electronic devices was made in a scale (1:16) remote-control tractor implemented with the electronic components of the prototype. The track width of the scale tractor was 127 mm, the height of the centre of gravity was 66 mm, and the mass of the scale tractor with the electronic components was 1062.2 g. The critical roll and critical pitch angles values were calculated for the control algorithm. These physical parameters of the tractor and the data from the sensors were used for implementation of the control algorithm. Fig. 7a shows the scale tractor with ROPS in the operating position. The Solid Works v. 2012 (SolidWorks Corp., Massachusetts, USA) computer program was used to design a three-dimensional (3D) model of the ROPS. The ROPS was built in acrylonitrile butadiene styrene using a 3D printer (Dimension BST 1200ES). The dimensions of the ROPS to the protection of the clearance zone for the driver have been calculated according to OECD Code 6 (2012). A solenoid coil was used to activate the spring that was deployed the ROPS. The scale tractor was operated on a test platform with a rising slope in laboratory conditions (Fig. 7b). The test platform has ascending and descending slopes, and also side slopes to test the scale tractor under different conditions. The measured and calculated data were transmitted to a personal computer via USB connection for further analysis and reporting.

[Figure 7. insert here].

3.2. Deployment time of HydraROPS test

A high speed camera (Faster Imaging Trouble Shooter TSHRMS, Artisan Technology Group, Champaign, IL, USA) was used to determine the time required to extend the structure. The hydraulic circuit of HydraROPS (Fig. 4) was installed in a Case tractor model 2120V that was used for this test. The tests were run in two sets of five deployments, five of them with the pressure accumulator disassembled and five of them with the pressure accumulator assembled. The deployment time was measured with the tractor at engine speed of 989 rev min^{-1}. Data were analysed by one-way ANOVA, and differences among means were determined with Fisher's (LSD) Multiple-Range Test using Statgraphics Plus, version 5.1., STSC Inc., Rockville, MD, (USA). All significant differences were determined at the 0.05 level of significance.

3.3. Electronic device test in real tractor

After testing the electronic device subsystem in the scale tractor, HydraROPS was then tested on a Case 2120V tractor. Field upset tests were conducted at the Agricultural Experimental Station of the Technical University of Cartagena. The path was 114 m with a maximum pitch angle of 33.59º and maximum roll angle of 25.65º.

4. Results and discussion

4.1. Electronic device test in scale tractor

Several factors were considered when deciding to build a scale safe tractor. The first one was to verify the correct operation of the electronic control subsystem, whilst the second one was its use for teaching tractor safety in an Open Day for secondary school children at the Technical University of Cartagena. The scale tractor has been used to teach basic knowledge such as: explaining the role that the centre of gravity plays in tractor overturns or explaining how to be protected during a tractor overturn.

4.2. Hydraulic circuit tests

Table 1 shows the deployment time of HydraROPS in the Case 2120V tractor with the pressure accumulator disassembled and assembled. In our experimental conditions, when the pressure accumulator was assembled in the hydraulic circuit, the deployment time was reduced by 71%. This result shows it is necessary to include a pressure accumulator in the hydraulic circuit, when hydraulic power is used to move the ROPS.

[Table 1. insert here].

A large reduction of the deployment time (71%) was produced by the use of the pressure accumulator in the hydraulic circuit of HydraROPS. However, with other technologies the time to extend the ROPS was less than with our prototype. In this sense, the spring-type system developed by Etherton et al. (2002) deployed the structure in 0.202 s, the telescopic structure developed by Silleli et al. (2008) deployed the structure in 0.160 s, and the airbag inflators system developed by Ballesteros et al. (2015) deployed the structure in 0.312 s. Therefore, we are working on a new hydraulic circuit to further reduce the deployment time of HydraROPS.

It should be noted that the literature offers findings about the overturning duration, which is 0.750 s according to Hathaway and Kuhar (1994) or 0.720 s according to Silleli et al. (2008). This time was approximately the same as the time required to deploy the HydraROPS prototype. In addition, by software it is possible to modify the stability index value to automatically start the deployment the HydraROPS with less slope, and thus save time.

4.3. Electronic device test in real tractor

Fig. 8 shows pitch angle and stability index in a rearward upset field test, and Fig. 9 shows roll angle and stability index in a sideward upset field test. The criterion that has been used for deployment of ROPS following the Eq. (1) was that when the pitch angle or roll angle or both are above the critical angle value the deployment of ROPS was activated. The experimental results showed that the ROPS was deployed at 102 s from the start of the route. In this time the combination of pitch angle (23.48 degrees) and roll angle (13.25 degrees) produced a stability index value below 20.

[Figure 8. insert here].

[Figure 9. insert here].

5. Conclusions

A hydraulic deploying mechanism for ROPS has been designed, constructed and tested to be used for agricultural tractors with a front-mounted ROPS. The deployment time of the mechanism was tested using an existing tractor ROPS. The results of the research show that the pressure accumulator assembled in the hydraulic circuit reduced the deployment time of ROPS by 71%. The deployment time was 0.743 s. The electronic control system can correctly predict overturn; in automatic mode, when the stability index value was below 40, an audible warning signal was switched on, and when the stability index value was below 20, the ROPS was deployed. The system sent geographic coordinates of the tractor's location to the emergency call centre, and information related to the movement of the ROPS will be recorded. This data can prove critical in reconstructing the accident.

HydraROPS has been patented (Ibarra Berrocal et al., 2015) and it has the advantage compared to other automatic deployment devices of protective structures that it can be installed on tractors equipped with certified rollover protective structures. The installation of HydraROPS in a tractor does not modify the protection structure, therefore a new certification of the protection structure is not necessary.

The results reported here are for a prototype device. The device is not yet marketable. Current plans are to continue developing HydraROPS employing a new hydraulic circuit to further reduce the deployment time of ROPS, and improve the control algorithm using the dynamic stability index developed by Liu and Ayers (1999).

Acknowledgements

The *Instituto de Seguridad y Salud Laboral de la Región de Murcia* for financing the project of "new safety devices in machinery".

References

Arana, I., Mangado, J., Arnal, P., Arazuri, S., Alfaro, J.R., Jarén, C., 2010. Evaluation of risk factors in fatal accidents in agriculture. Span. J. Agric. Res. 8 (3), 592-598.

Ballesteros, T., Arana, I., Pérez, A., Alfaro, J.R., 2013. E2D-ROPS: Development and tests of an automatically deployable, in height and width, front-mounted ROPS for narrow-track tractors. Biosyst. Eng. 116 (1), 1–14.

Ballesteros, T., Arana, I., Pérez, A., Alfaro, J.R., 2015. Development and validation of automatically deployable ROPS based on airbag inflator technology. Biosyst. Eng. 130, 92 -105.

DTAEBT, 2015. Universal rollover risk warning device. http://www.dtaebt.com (access January 15th, 2015).

Etherton, J., Cutlip, R., Harris, J., Ronaghi, M., Means, K., Howard, S., 2002. Dynamic performance of the mechanism of an automatically deployable ROPS. J. Agric. Saf. Health 8(1), 113–118.

Hathaway, L., Kuhar, J., 1994. Farm and ranch safety management. Moline, Il: Deere and Company Service Publications.

HOSTA, 2004. Tractor Stability. National safe tractor and machinery operation program. Task Sheet 4.12. The Pennsylvania State University, 1-4.

Hoy, R.M., 2009. Farm tractor rollover protection: why simply getting rollover protective structures installed on all tractors is not sufficient. J. Agric. Saf. Health 15(1), 3-4.

Ibarra Berrocal, I., Martin Gorriz, B., Ojados Gonzalez, D., Miguel Hernandez, B., Caro Garcia, F., Morales Sanchez, P., Morente Sánchez, A., 2015. Sistema de protección antivuelco para vehículos agrícolas. Spanish Patent ES2452489 [In Spanish].

Liu, J., Ayers, P.D., 1998. Application of a tractor stability index for protective structure deployment. J. Agric. Saf. Health Special Issue 4(1), 171-181.

Liu, J., Ayers P.D., 1999. Off-road vehicle rollover and field testing of stability index. J. Agric. Saf. Health 5, 59-79.

Liu, B., Koc, A.B., 2013. SafeDriving: A mobile application for tractor rollover detection and emergency reporting. Comput. Electron. Agric. 98, 117–120.

Liu, B., Koc, A.B., 2015. Field tests of a tractor rollover detection and emergency notification system. J. Agric. Saf. Health 21(2), 113-127.

Martin-Gorriz, B., Ibarra Berrocal, I., Mínguez Samper, A., Morente Sánchez, A., 2012. Accidentes por vuelco de tractor de la Región de Murcia: propuestas para su reducción. Formación de Seguridad Laboral 123, 70-71 [In Spanish].

Nichol C. I., Sommer H. J., Murphy D. J., 2005. Simplified overturn stability monitoring of agricultural tractors. J. Agric. Saf. Health, 11(1), 99-108.

OECD Code 6, 2012. OECD Standard Code for the official testing of front mounted roll-over protective structures on narrow-track wheeled agricultural and forestry tractors. Paris: Organisation for the Economic Co-operation and Development.

Powers, J.R., Harris, J.R., Etherton, J.R., Snyder, K.A., Ronaghi, M., Newbraugh, B.H., 2001. Performance of an automatically deployable ROPS on ASAE tests. J. Agric. Saf. Health 7 (1), 51–61.

Silleli, H., Dayıoglu, M. A., Gultekin, A., Ekmekci, K., Yildiz, M. A., Akay, E., Saranli G., 2007. Anchor mechanism to increase the operator clearance zone on narrow-track wheeled agricultural tractors: prototype and first tests. Biosyst. Eng. 97, 153-161.

Silleli, H., Dayıoglu, M.A., Gültekin, A., Saranlı, G., Yıldız, M.A., Akay, E., Ekmekçic, K., 2008. Anchor mechanism to increase the operator clearance zone on narrow-track wheeled agricultural tractors: Static and field upset test results. Biosyst. Eng. 99 (2), 196–204.

SWA, 2011. Fatalities due to working with tractors, Australia 2003-07. Government of Australia. http://www.safeworkaustralia.gov.au (access January 15th, 2015).

Tables and Figure Captions

Table 1. Deployment time of HydraROPS in Case 2120V tractor.

Figure 1. Schematic diagram of the two possible modes to switch on HydraROPS.

Figure 2. System architecture of HydraROPS.

Figure 3. Flowchart for the algorithm used by the microcontroller.

Figure 4. Hydraulic circuit of HydraROPS.

Figure 5. Hydraulic and electronic components of HydraROPS installed in a Case 2120V tractor. (a) hand box panel, (b) electronic box, (c) hydraulic cylinder, (d) electro-hydraulic circuit of HydraROPS, (e) pressure accumulator, (f) exterior protection.

Figure 6. Case 2120V tractor with HydraROPS prototype installed. (a) ROPS in retracted position (b) ROPS in deployed position.

Figure 7. (a) scale tractor, (b) test platform.

Figure 8. Pitch angle and stability index in a rearward upset field test.

Figure 9. Roll angle and stability index in a sideward upset field test.

Table 1. Deployment time of HydraROPS in Case 2120V tractor.

Type of test	**Time (s)**	
	Average value recorded of the 5 tests	**Maximum value recorded of the 5 tests**
Pressure accumulator disassembled	2.575 a	2.599
Pressure accumulator assembled	0.733 b	0.743

Treatments with different letters had significant differences according to Fisher (LSD) at 95.0%.

Figure 1

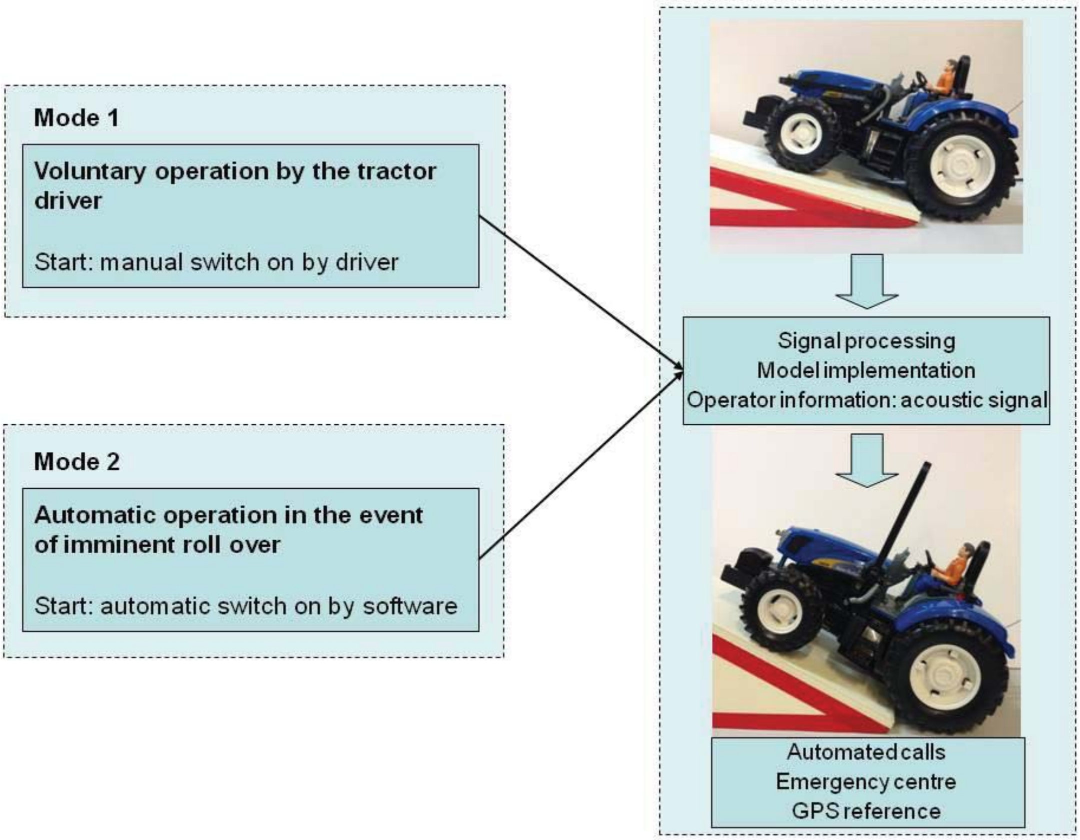

Figure 1. Schematic diagram of the two possible modes to switch on HydraROPS.

Figure 2

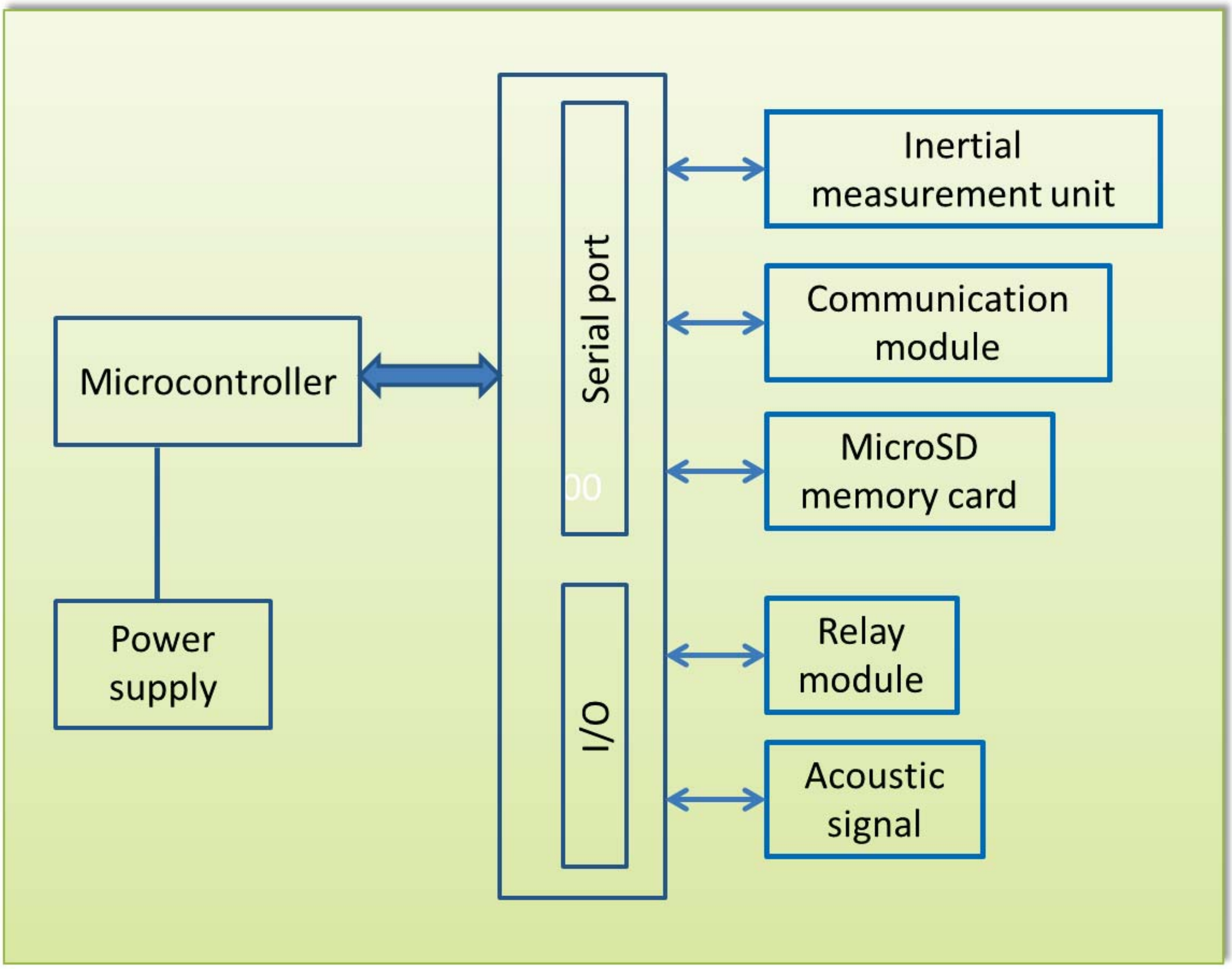

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Figure 3

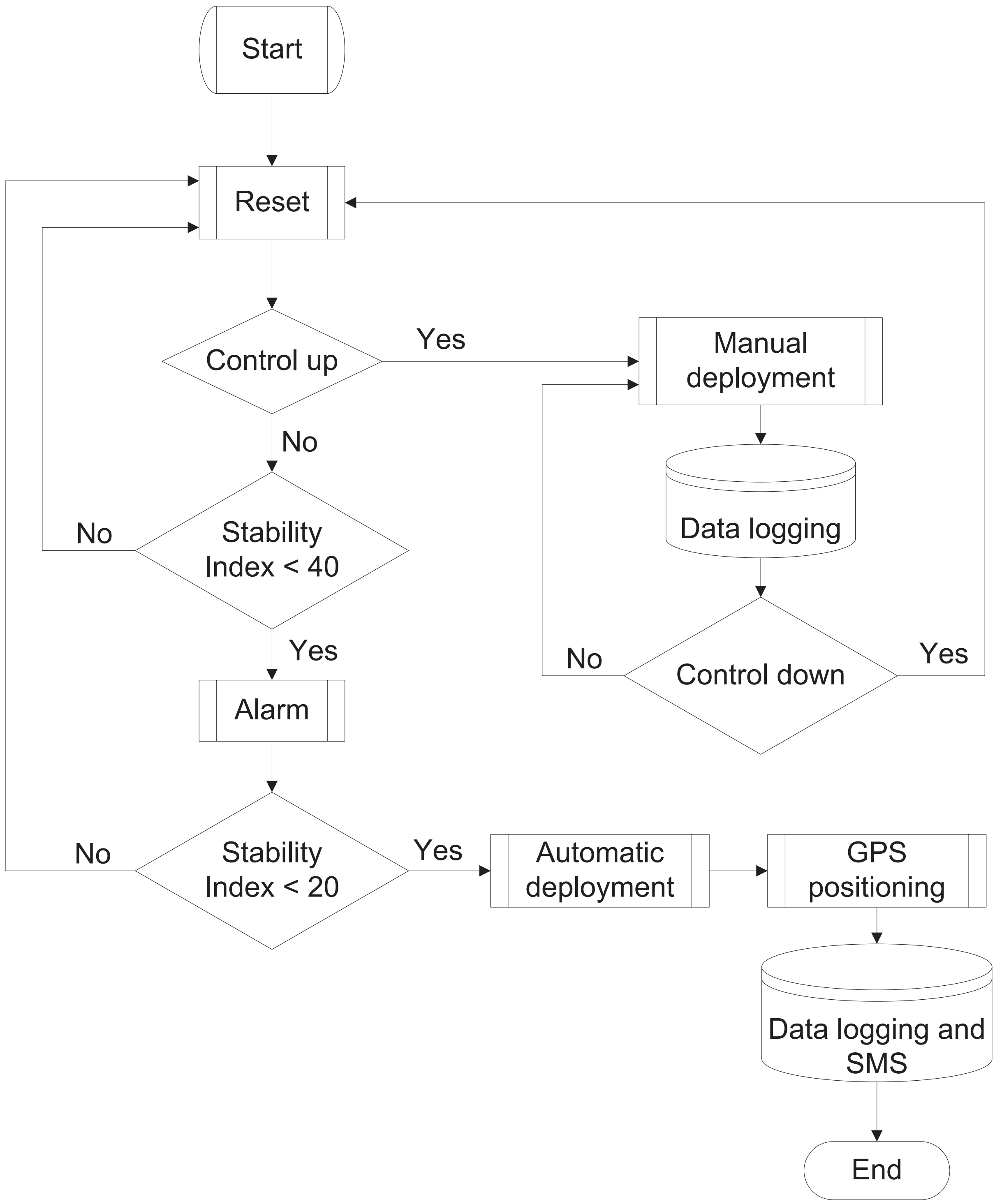

Figure 3. Flowchart for the algorithm used by the microcontroller.

Figure 4

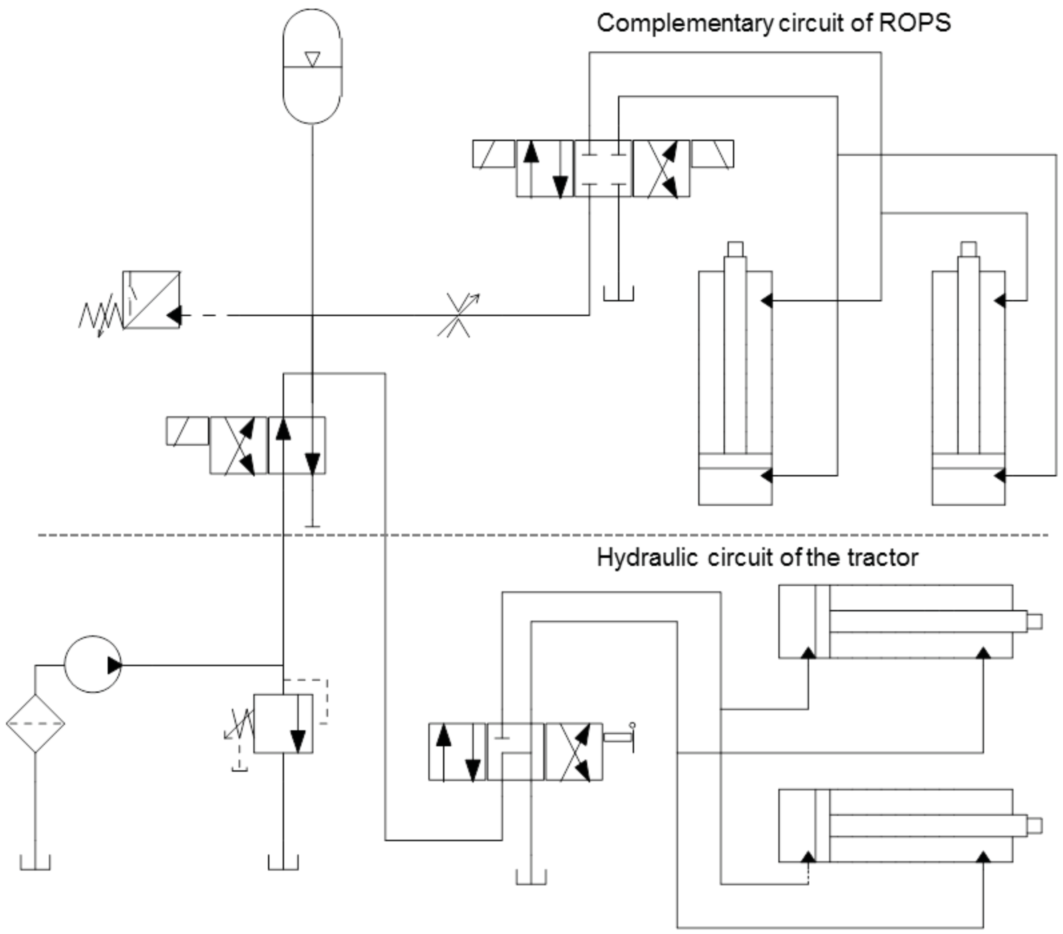

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Figure 5

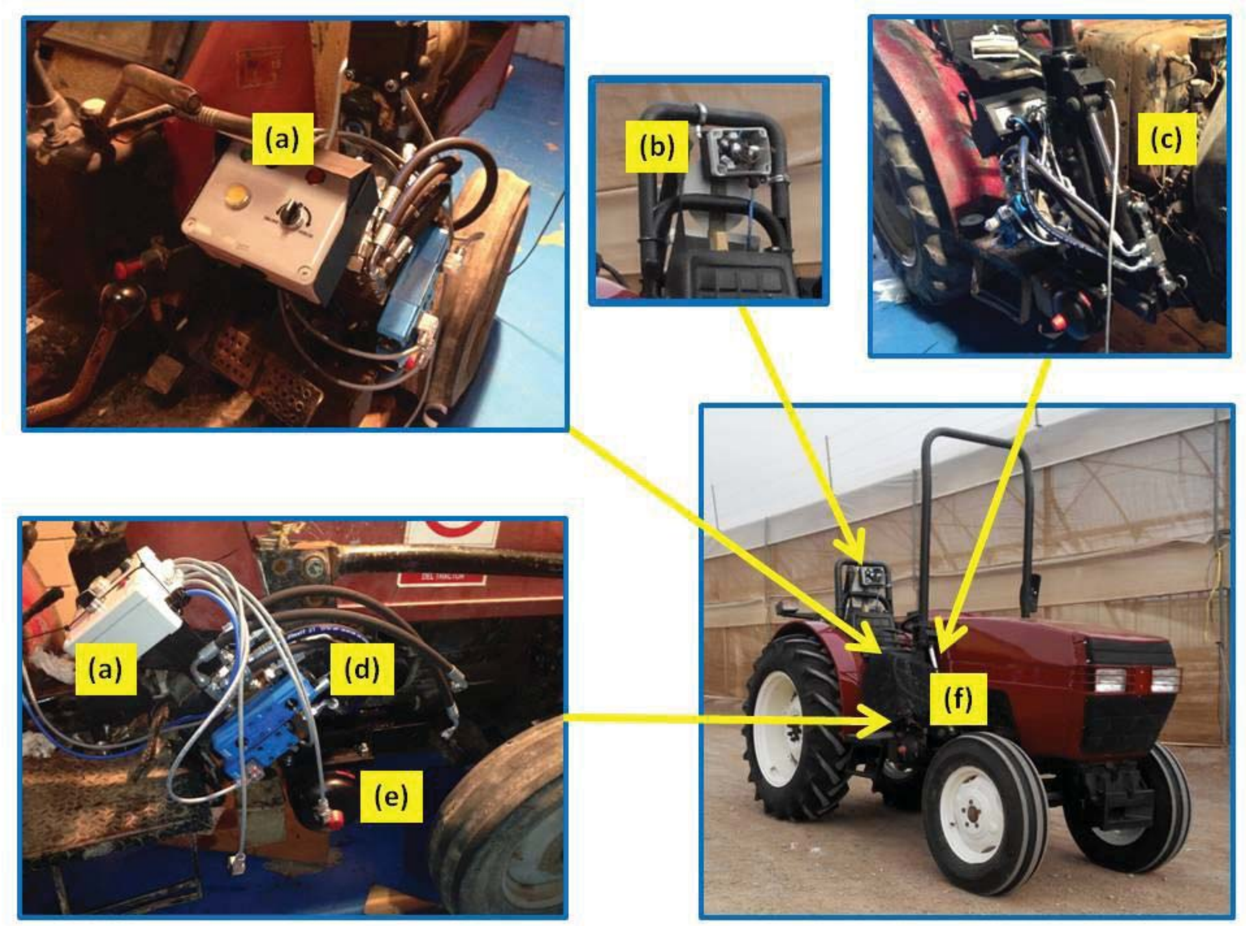

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Figure 6

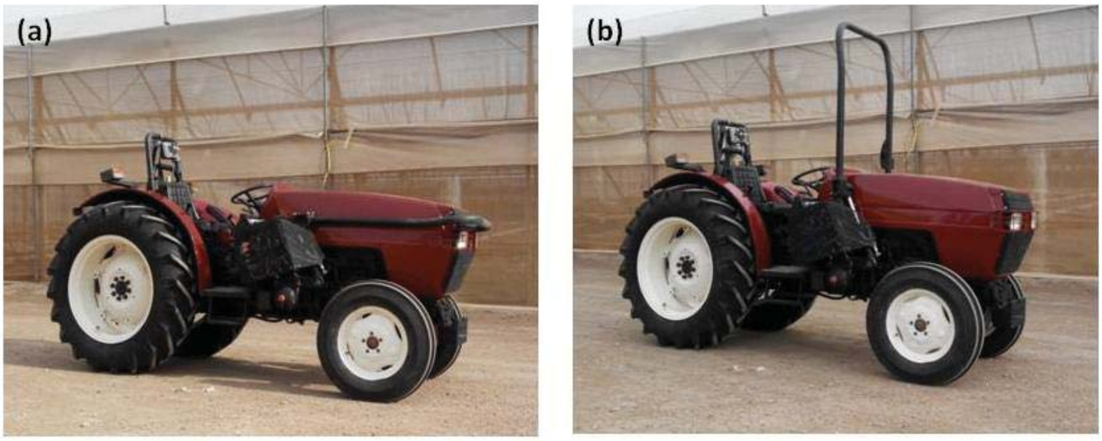

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Figure 7

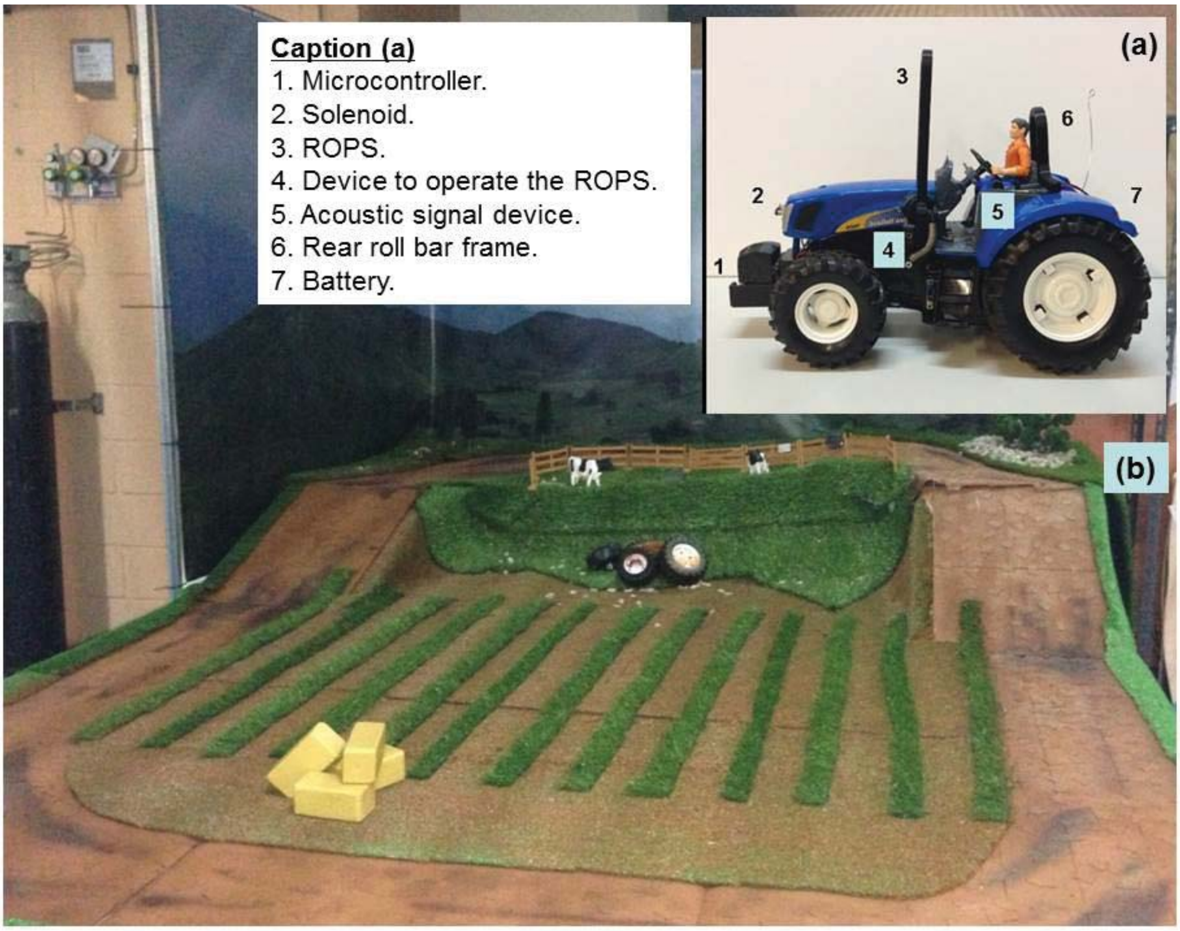

Figure 7. (a) scale tractor, (b) test platform.

Figure 8

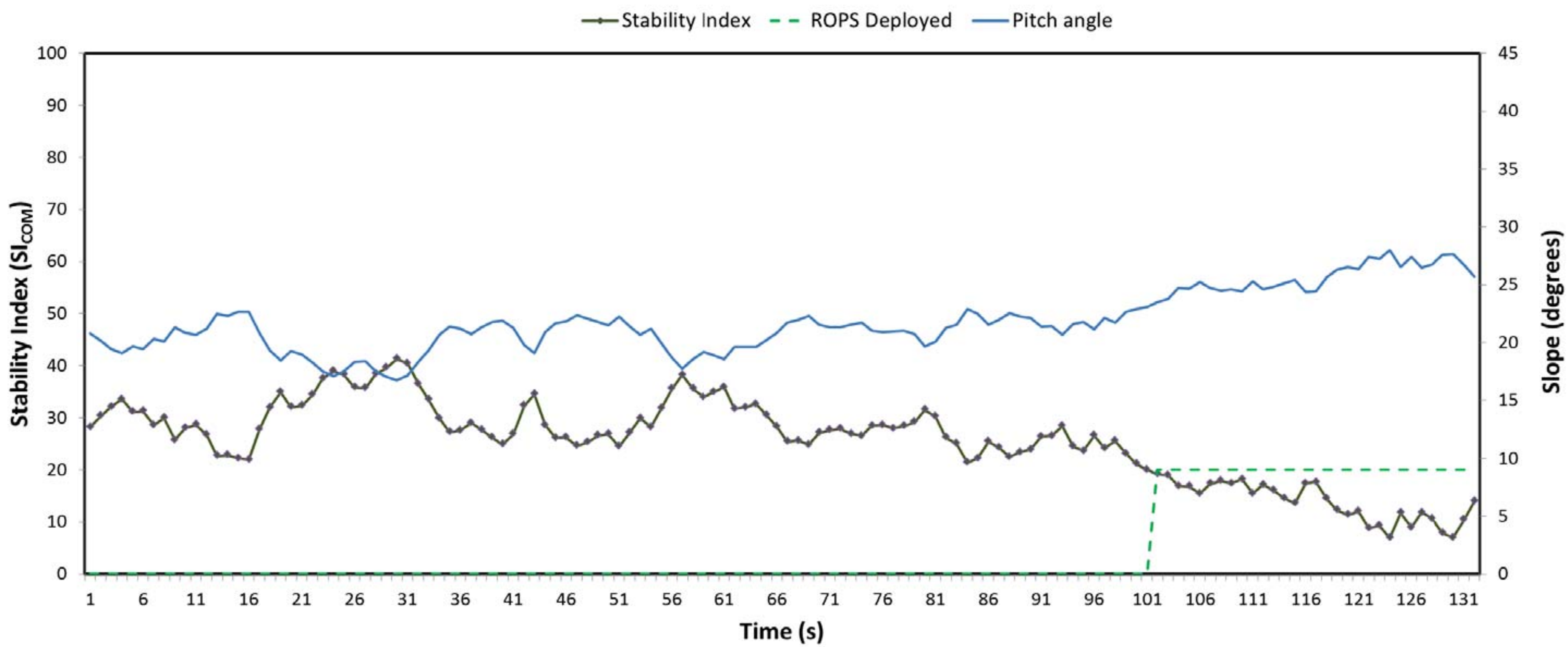

Figure 8. Pitch angle and stability index in a rearward upset field test.

Figure 9

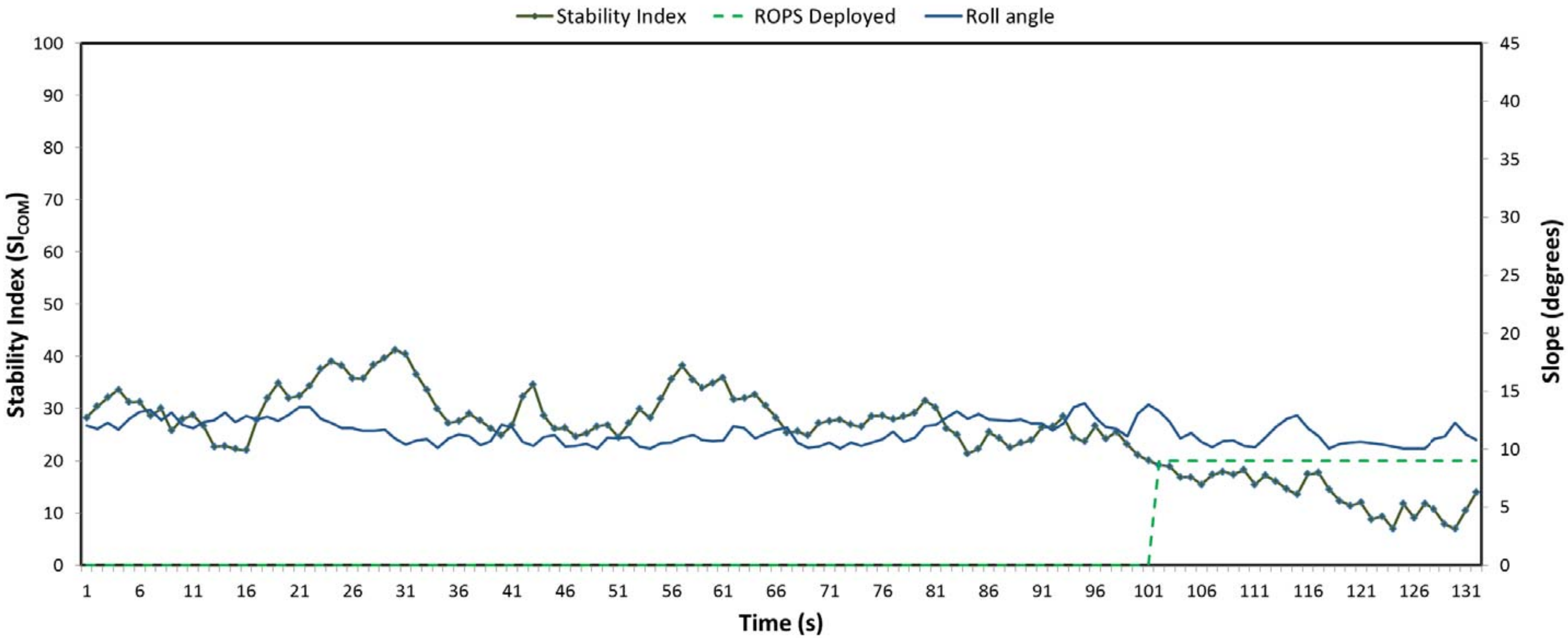

Figure 9. Roll angle and stability index in a sideward upset field test.