AgroGuardian: An All-Terrain Vehicle Crash Detection and Notification System

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Research

HIGHLIGHTS

- Off-road ATV incidents can be problematic due to long EMS alert times.
- An ATV crash-detection-and-report system is expected to reduce EMS response time.
- The developed system can accurately detect ATV rollovers.
- The alert time of our system is 10 times faster than the national U.S. average.
- Any rider using our system is 3 times more likely to survive an off-road crash.

ABSTRACT. *All-Terrain Vehicle (ATV) incidents are a common cause of injury and death in the agricultural industry in the United States. Many ATV off-road crashes on farms and ranches may result in trauma requiring immediate care, but the injured rider is unable to seek help due to their injuries. Moreover, many of these crashes occur in isolated areas that may be difficult to access and have unreliable cellular phone service, making contact with emergency medical services (EMS) challenging. This study aimed at developing and testing a low-cost ATV crash detection device (AgroGuardian) that immediately alerts EMS and emergency contacts, even when the rider is unable to take action and/or there is no cellular phone service available. AgroGuardian includes an embedded data logging system, a smartphone application, and a remote database. The embedded system includes an Inertial Measurement Unit (IMU) for attitude estimation, a Global Positioning System (GPS) for location estimation, and a Rock7 modem for off-board communication. A smartphone application was developed for the users to input information about their vehicle (e.g., make and model) and emergency contacts. Also, it allows them to interact with their ATV data. An emergency signal along with the ATV's coordinates is transmitted through the Rock7 modem and received in the remote database when a rollover is detected by the system. This emergency signal is then processed and sent to EMS and emergency contacts. Our results indicated that the device: (1) is unlikely to miss an ATV rollover;*

Submitted for review on 1 September 2023 as manuscript number JASH 15801; approved for publication as a Research Article by Associate Editor Dr. Aaron Yoder and Community Editor Dr. Michael Pate of the Ergonomics, Safety, & Health Community of ASABE on 23 February 2024.

Citation: Khorsandi, F., De Moura Araujo, G., & Ferreira Lima dos Santos, F. (2024). AgroGuardian: An all-terrain vehicle crash detection and notification system. *J. Agric. Saf. Health, 30*(2), 53-74. https://doi.org/10.13031/jash.15801

(2) has a fast EMS notification time (40.7 s); and (3) the ATV localization system presented an average error of 2.34 m.

Keywords. *ATV, EMS alert time, Farm, Off-road incidents, Quadbike, Rollover.*

All-Terrain Vehicle (ATV) incidents are a common cause of injury, death, and financial loss in the United States (Jennissen et al., 2016). The Consumer Product Safety Commission (CPSC) estimates that over 700 ATV-related fatalities and 90,000 emergency department visits occur annually (CPSC, 2018). In addition, the annual cost of lives and health care from ATV-related incidents increased almost five times by 2016, reaching more than 22 billion dollars spent (Helmkamp et al., 2009; Helmkamp et al., 2008; Qin et al., 2016). One-half of all ATV-related occupational injuries and 65% of all ATV-related occupational fatalities occur in agriculture (Helmkamp et al., 2012; Lagerstrom et al., 2015). These incidents are often associated with a variety of activities inherent to agricultural work, including herding and herbicide spraying (Jennissen et al., 2020; Neves et al., 2018).

To determine strategies to prevent these incidents, several studies have focused on identifying risk factors for ATV-related crashes (Balthrop et al., 2009; Carman et al., 2010; Doud et al., 2017; Lagerstrom et al., 2016; Neves et al., 2018). For instance, the crash location is associated with the likelihood and severity of ATV-related injuries and fatalities (Hall et al., 2009; Lagerstrom et al., 2015; Lagerstrom et al., 2016; Lin and Blessing, 2018; Qin et al., 2017). Although roadway crashes have significantly increased over the past several decades (Denning et al., 2013a; Denning and Jennissen, 2015), ATV-related deaths are still common in off-road (on rough terrain) crashes (Denning et al., 2013b; Killingsworth et al., 2005; Lagerstrom et al., 2015; Qin et al., 2017; Rodgers, 2008), particularly on farms or ranches (McIntosh et al., 2016). Moreover, seven out of the top ten states with the highest number of deaths reported from 2007 to 2011 are among the ten states with the highest percentage of the population living in rural areas (areas with land usage classified as rural) in 2010 (U.S. Bureau of the Census, 2010; Williams et al., 2014).

The majority of ATV off-road crashes are either rollovers or collisions (Balthrop et al., 2007; Cavallo et al., 2015; Denning et al., 2013b; Helmkamp et al., 2011; Lin and Blessing, 2018). Rollover incidents on farms (or ranches) often result in the rider being pinned underneath the vehicle, which leads to death by mechanical asphyxia in 42% of the cases, where the operator was pinned underneath the vehicle due to a rollover (McIntosh et al., 2016). On the other hand, collisions can culminate in blunt trauma to the torso (49% of the time) or head (13% of the time). (Grzebieta et al., 2015a; Lin and Blessing, 2018; McIntosh et al., 2016). Mechanical asphyxiation and blunt trauma are the principal causes of ATV-related deaths on farms and ranches. These traumatic injuries often require immediate medical attention; otherwise, the chances of survival may be dramatically reduced (McIntosh and Patton, 2013; University of Florida Health, 2020). Indeed, mechanical asphyxia and traumatic injuries were widely reported as the principal causes of death in ATV-related crashes on farms and ranches (Denning et al., 2013b; Denning and Jennissen, 2015; Grzebieta et al., 2015b; Lin and Blessing, 2018; McIntosh et al., 2016).

The timing before first aid initiation as well as EMS arrival may be a critical factor in off-road ATV-related fatalities. A previous study reported that nearly 70% of ATV-related deaths occurred within three hours of the incident (McIntosh and Patton, 2013). Several studies have shown that many ATV crashes occur in areas beyond which an ambulance could respond and drive back to a hospital within an hour (Balthrop et al., 2009; Qin et al., 2016; Qin et al., 2017). Other problems that can further delay medical treatment include (1) poor cellular phone service, making it difficult to call for help; (2) difficulty locating and obtaining access to the crash site by emergency medical services (EMS); and (3) challenges in extracting injured patients from a remote site and transporting them to the nearest hospital. (Balthrop et al., 2009; Qin et al., 2016; Rodgers, 2008).

A device on the ATV that would be able to monitor factors that can lead to a crash, detect a crash when it happens, and then promptly notify EMS could effectively address these issues. Speeding and sloped terrain are important causes of ATV crashes. Some studies have shown steep slopes as a leading cause of ATV rollovers in agricultural settings (Carman et al., 2010; Cavallo et al., 2015; Milosavljevic et al., 2011). Thus, parameters such as the vehicle's speed, acceleration, and attitude (roll, pitch, and yaw) are important variables to be monitored for crash detection.

Many off-road crashes involving ATVs result in injuries that require immediate care. However, the riders are often unable to seek help because they are severely injured. Further aggravating the issue, several crashes occur in isolated areas without reliable and constant cellular service. Thus, making it challenging to contact EMS promptly. Although ATV rollover detection devices are commercially available in other countries, this technology is expensive and not available in the U.S. Therefore, there is a need for a low-cost ATV crash-detection device that promptly alerts EMS, even when riders are unable to take action and/or there is no cellular phone service available.

Our long-term goal is to decrease the severity of injuries and the number of fatalities in ATV-related crashes. Our study objective, which is a step towards attaining our long-term goal, was to develop an automatic ATV rollover detection and notification device we have named AgroGuardian that promptly directs EMS to the crash scene, even when riders are unable to take action and there is no cellular phone service available. The use of such a device should reduce EMS alert time and increase the likelihood of injured riders surviving and sustaining less severe injuries (Balthrop et al., 2009; Qin et al., 2016, 2017). Other specific aims were to develop and insert applications in AgroGuardian for safety, including an autonomous shut-off system, an anti-theft device, geo-fencing capabilities, and tracking of ATV speed and acceleration. In addition, we planned to validate the successful performance of AgroGuardian in detecting rollover, notifying a base site of a crash, providing accurate crash location data, and performing other device functions such as data recording and geo-fencing.

Materials and Methods

Our team's development of AgroGuardian involved a collaborative process, focusing on creating a comprehensive safety system for ATV riders. We engineered AgroGuardian with a multifaceted approach: it features an embedded data logging system and control unit, a user-friendly smartphone application (iOS), and a robust cloud database (fig. 1).

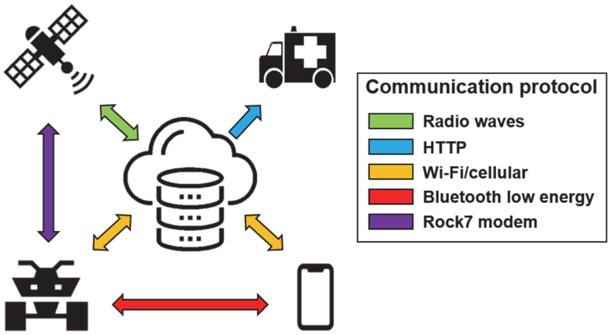


Figure 1. AgroGuardian System and Communications.

The embedded system was used for two main tasks: (1) monitor and record ATV riding parameters (e.g., vehicle's location, trip history, velocity, acceleration, and attitude); and (2) trigger an emergency alert when a crash or dangerous riding conditions are detected.

Two distinct smartphone applications (apps) were developed, one for general public use (GP) and one for research purposes (RP). The GP app was created to provide users with an interface to interpret and interact with their ATV data and provide custom services such as rider credentials, customized geo-fencing, and danger alerts. In addition to the features present in the GP app, the RP app allows users to set system parameters such as data recording frequency and have fast data access for in-site data analysis and interpretation. Lastly, the cloud database was built to remotely store, manage, and transfer users' data to smartphone applications. In the next sections, we present a detailed description of the developed systems.

Embedded Data Logging System and Control Unit

A Raspberry Pi 4 Model B (RPi, 4GB) single-board computer (Adafruit, New York, NY, USA) was used as the controller of the embedded system. The RPi uses a 1.5GHz 64-bit quad-core Arm Cortex-A72 CPU and has an 802.11 ac/n wireless LAN, and Bluetooth 5.0. In addition, the RPi has several ports for communicating with peripherals, including HDMI, USB, SD Card reader, and general-purpose input/output (GPIO) pins. The embedded data logging system and control unit consists of five systems, namely: Rollover Detection, Rollover Report, Vehicle Tracking, and Geo-fencing. A portable battery (Anker PowerCore II 20000) was used to supply power to the system. When the ATV engine was turned on, the ATV's battery was used to recharge the portable battery.

Rollover Detection

Rollover occurrences were determined by comparing the ATV's static stability angles to the ATV's roll and pitch angles in real time. When either roll or pitch angles were higher than the ATV's lateral or longitudinal stability angles, respectively, an internal counter would be updated. When the counter was above a certain threshold (5 seconds), the system would trigger the emergency system, alerting EMS. The importance of implementing a counter is explained by the fact that false positive rollover detection may occur. The counter circumvents erroneous detections by evaluating a sequence of events instead of a single occurrence. Moreover, the choice for the threshold (5 seconds) was based on the approximate time an ATV takes to rollover. Although, ATV rollover crashes usually take less than a second (Heydinger et al., 2019), an assurance margin of around 4 seconds was adopted for this study. The scheme of the rollover detection system is illustrated in figure 2.

The ATV static stability angles are the critical angles at which an ATV begins to roll (either sideways or forward/rearward). Lateral (side) and longitudinal (rear/front) stability angles are important measures of the relative stability of an ATV and have been used to describe the rollover propensity of specific vehicles (Grzebieta et al., 2015c; Grzebieta, 2015a; Heydinger et al., 2016). These angles are generally determined through tilt table tests or calculated based on the center of gravity location, usually determined by the lifting axle method. The static stability angles used in the present study were determined based on the results of previous studies (Grzebieta et al., 2015c; Heydinger et al., 2016).

The ATV's attitude (including roll and pitch) was measured with an Inertial Measurement Unit (IMU – model LSM9DS1, manufacturer Adafruit). To improve the accuracy and robustness of the vehicle's attitude estimate, a Madgwick filter (Madgwick et al., 2011) was utilized. This filter fuses gyroscope, accelerometer, and magnetometer measurements to calculate the vehicle's attitude. The vehicle's attitude is initially estimated by integrating gyroscope measures, which inherently yields drift in the long term. The long-term drift from the gyroscope integration is compensated by the accelerometer estimates of attitude. The magnetometer measures are used to compensate for magnetic distortions from potential sources of interference around the sensor, such as electronic devices (for instance, a GPS sensor) and metal structures (e.g., the ATV's frame).

In case the system fails to detect a rollover, or if EMS is required without an actual rollover, the rider can manually activate the emergency alert system. Redundancy measures have been incorporated through a backup system, featuring an emergency button integrated into the smartphone apps. Upon pressing the button, an emergency signal is transmitted to the controller via Bluetooth low energy (BLE). This manual override allows riders to trigger the emergency alert independently in situations where the rollover detection system, based on the IMU, may have failed.

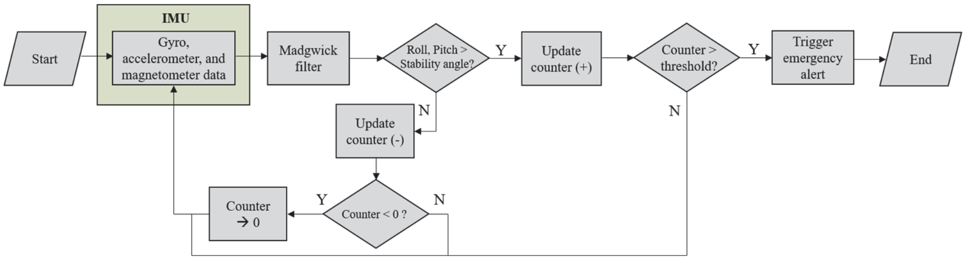


Figure 2. Rollover detection process.

Rollover Detection Performance Assessment

Fifteen angle values larger and 15 angle values smaller than the static stability threshold for side rollover (roll) of a 2018 Honda Rancher TRX 500 4x4 ATV were randomly selected to assess the performance of the rollover detection system. The stability threshold values were retrieved from Grzebieta et al. (2015c). The threshold for longitudinal rollover was calculated as the average between the left and right rollover thresholds. AgroGuardian's embedded system was manually tilted and kept at the selected angles. A binary score was assigned to each test (angle value) according to the following logic:

$$\text{Score} = \begin{cases} 0, \text{ if rollover is detected when } \theta < T \text{ (false positive)} \\ 0, \text{ if rollover is not detected when } \theta > T \text{ (false negative)} \\ 1, \text{ if rollover is not detected when } \theta < T \text{ (true negative)} \\ 1, \text{ if rollover is detected when } \theta > T \text{ (true positive)} \end{cases}$$

where θ is the random angle at which the system was tilted and T is the lateral (side) stability angle (retrieved from Grzebieta et al. [2015c]). A similar procedure was replicated to evaluate the system's performance in detecting rear/front rollovers (pitch).

Rollover Report – Emergency Alert

Rollovers were reported to *Noonlight*, which is a third-party platform that can trigger requests to emergency services. The choice for *Noonlight* was based on its compatibility with the iOS platform and because it is a low cost service. In summary, when a rollover is detected by the embedded system (1), the Raspberry Pi sends a message off-board via the Iridium Satellite Network (2), which is designed to provide communication services in areas where traditional cellular coverage may be limited or unavailable, that triggers an emergency alert pre-set on the cloud database (3). Then, the database sends a *HyperText Transfer Protocol* (HTTP) request to *Noonlight* (4), informing the crash occurrence and location. *Noonlight's* certified operators immediately text or call the user. If the user cannot cancel the alert or does not respond, *Noonlight's* operators will contact EMS (5). A scheme of the accident report procedure is illustrated in figure 3.

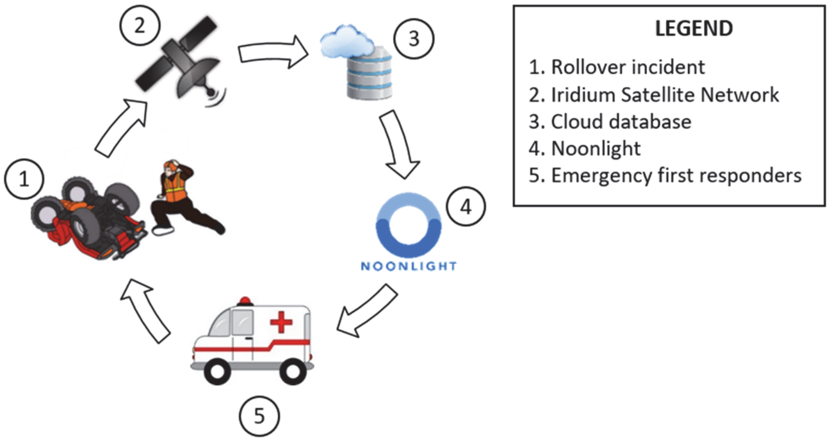


Figure 3. Emergency alert.

The system's capability and promptness in reporting a crash were evaluated based on the alert time. The alert time was defined as the time it took from the rollover incident occurrence moment until *Noonlight*'s confirmation of AgroGuardian's emergency alert.

It is important to clarify that a rollover can occur at various places, and the specific location of the incident can significantly affect the ability of the system to send an off-board emergency signal. For instance, a rollover can occur inside an orchard with large trees or near a building (e.g., a barn). Trees are physical barriers that can potentially block the signal of AgroGuardian's antenna. For this reason, we performed the rollover simulations outdoors, in an area surrounded by tall trees and buildings with an approximate height of 12 m (36 ft). We deem that the selected experimental area is representative of potential locations in which a rollover would occur on farms and ranches.

Vehicle Tracking System

A Global Positioning System (GPS – model Ultimate GPS Breakout v3, manufacturer Adafruit) and the IMU recorded the vehicle's location, speed, acceleration, and trip history. Communication between the IMU and the RPi was implemented via a *Serial Peripheral Interface* (SPI) connection, and communication between the GPS and the RPi was implemented through a *Universal Asynchronous Receiver Transmitter* (UART) GPIO pin (fig. 5).

Due to the environment of some ATV off-road crashes (e.g., dense woods), GPS signals might be unavailable or yield inaccurate measures. To address this issue, IMU data (which allows continuous position tracking) was fused with GPS data through an Unscented Kalman Filter (UKF) (Brossard et al., 2020). The UKF is a non-linear version of a Kalman Filter (Gomez-Gil et al., 2013; Kalman, 1960), which is an algorithm that combines multiple sensor information to estimate the state of a system, such as the vehicle's position (Leung et al., 2011). The fundamental advantage of the UKF over the Kalman Filter is that it works for non-linear systems, which is the case for most robots and sensors (S. G. Vougioukas, personal communication, 2019).

Vehicle Tracking Performance Assessment

Vehicle tracking metrics were evaluated with a 2018 Honda Rancher TRX 500 4x4 ATV equipped with AgroGuardian and a Real-Time Kinematic Global Navigation Satellite System (GNSS) receiver (RTK – model Piksi Multi GNSS, manufacturer Swift Navigation).

Position

Data from both devices were collected during a ride in a straight line of 30.5 m (100 ft) at selected speeds of 2.23, 3.57, and 5.36 m s^{-1} (5, 8, and 12 mph, respectively). Those speeds were chosen because they are the most common ATV speeds, according to a survey among 79 interviewees (Polaris ATV Forum, 2015). In total, there were three replicates for each selected speed.

The RTK receiver positions were adopted as a reference to calculate the relative deviation in the GNSS module positions. AgroGuardian's position estimate accuracy was evaluated based on the Euclidian distance between AgroGuardian's position estimate and the RTK's data. The coordinates of both receivers were converted to UTM coordinates using the WGS 84 datum. The deviation in meters obtained by the GNSS module from the RTK was calculated using equation 1.

$$\bar{D} = \frac{1}{n}\sum_{i=1}^{n}\sqrt{\left(X_{RTK} - X_{agro}\right)^2 + \left(Y_{RTK} - Y_{agro}\right)^2} \tag{1}$$

where

$\bar{D}$ = average position deviation in AgroGuardian's GPS module to the reference device (m)

n = number of observations

X_{RTK} and Y_{RTK} = point coordinates obtained by the RTK module

X_{agro} and Y_{agro} = point coordinates obtained by the GNSS module.

Velocity

In order to maintain a constant speed during the experimental trials, the ATV was equipped with a QuadCruise control unit (MC S2580E, MCCruise). The control unit of the cruise control system consists of a computer unit, an electric throttle servo, a Cable Interface Unit (CIU), and a Bluetooth module for remote controls (MCCruise, 2018). More information about the installation and operation of this device is available from a previous study (Chou et al., 2022).

Although the QuadCruise controlled the ATV speed remotely, an operator was always riding the vehicle for safety purposes. In summary, the vehicle was accelerated to the desired speed (which was adjusted by the operator) and then ridden for at least 10 seconds to allow the GPS module to track a stable velocity (fig. 4). Three pre-set speeds were evaluated: 2.23, 3.57, and 5.36 m s^{-1} (5, 8, and 12 mph, respectively), with three replicates for each speed. The average velocity error was calculated according to equation 2.

$$\bar{V}_{error} = \frac{1}{n}\sum_{i=1}^{n}\left|V_{RTK\ i} - V_{agro\ i}\right| \tag{2}$$

where

$\bar{V}_{error}$ = average velocity error (m s^{-1})

n = number of observations

$V_{RTK\ i}$ = RTK receiver velocity (m s^{-1})

$V_{Agro\ i}$ = AgroGuardian velocity (m s^{-1}).

The majority of the observations occurred outside of the constant speed zone (e.g., start/end of data collection with ATV stationary, speeding zone), which could add bias to the estimation of $\bar{V}_{error}$, since the number of observations outside the constant speed zone is higher than the number of observations in the constant speed zone. For this reason, only observations in the constant speed zone were used in the calculation of $\bar{V}_{error}$.

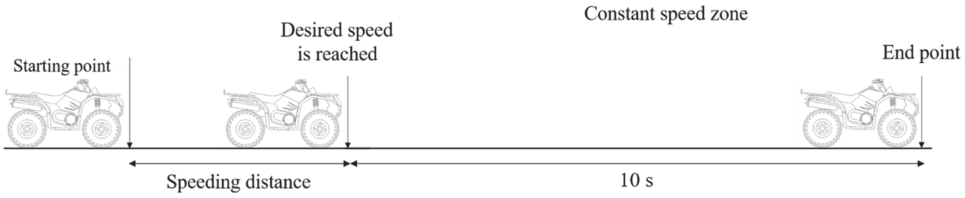


Figure 4. Schematic of the procedure to evaluate the "Velocity Measurement performance" in AgroGuardian.

The field tests conducted to evaluate the vehicle tracking system performance were carried out in the same experimental area described in the section titled “Rollover Report – Emergency Alert.”

Geo-Fencing

Geo-fencing was implemented in AgroGuardian as a polygon shape. The vehicle is only allowed within the polygon, and when it exits the boundary, the user receives a warning message through the smartphone application (both GP and RP applications included this feature). Users can create customized geo-fencing for each specific ATV via smartphone apps. A map pops up, and the user needs to indicate the vertices of the desired polygon on the screen.

Geo-fencing is important because it creates an extra layer of verification, informing the user when a vehicle is entering a zone that it was not supposed to. For instance, a rider can unknowingly enter an unauthorized area. This situation puts riders at risk, as they might be subject to encountering wild animals or unintentionally trespassing on private properties.

In addition to improving riders’ safety, geo-fencing can be used for theft detection/prevention. For instance, if users detect that the vehicle is exiting a pre-set boundary without their consent, they can remotely shut the engine off by sending a signal to RPi that activates the engine shut-off system.

A relay (model FeatherWing, manufacturer Adafruit) was implemented in the system to control the flow of current from the ATV’s battery to its engine (engine kill switch). When the user activated the “engine shut off button,” implemented in both the GP and RP apps, the relay would interrupt the passage of current, thus shutting the ATV’s engine off.

Geo-fencing Performance Assessment

Geo-fencing was tested with three different polygon shapes: a rectangle, a circle, and an irregular polygon. A binary score was assigned to each test according to the following logic:

$$\text{Score} = \begin{cases} 0, \text{if vehicle is detected inbounds when the vehicle is out of bounds (false positive)} \\ 0, \text{if vehicle is detected out of bounds when the vehicle is inbounds (false negative)} \\ 1, \text{if vehicle is detected out of bounds when the vehicle is out of bounds (true negative)} \\ 1, \text{if vehicle is detected inbounds when the vehicle is inbounds (true positive)} \end{cases}$$

The coordinates of the virtual areas were collected from Google Maps (Alphabet Inc., Mountain View, CA, USA). The first polygon (regular shape) was delimited by the coordinates of its four vertices, whereas the second polygon was defined by 23 points collected around the perimeter of a roundabout, and the last polygon (irregular) was defined by 22 points. The choice of the number of points used was based on the minimum number of points needed for the proposed shape.

System Specifications

All the electronic components of the embedded system (fig. 5) were placed inside a custom-manufactured enclosure, resistant to vibration and dust, which was installed on the rear rack of the ATV. The antenna of the GNSS was attached to the ATV front chassis. The acquisition prices, specifications, and manufacturers of the system's components are shown in table 1.

Table 1. Summary of the components used in AgroGuardian's embedded system.

Quantity	Component	Specifications	Manufacturer	Units Cost (US$)*
1	Raspberry Pi 4	1.5GHz 64-bit quad-core Arm Cortex-A72 CPU, 4GB RAM, 802.11 ac/n wireless LAN, Bluetooth 5.0, and 40 general-purpose input/output pins	Adafruit, New York, NY, USA	65.00
1	GNSS module	Frequency sampling rate 10 Hz, and input voltage of 3.3 or 5 V	Adafruit, New York, NY, USA	39.95
1	GNSS antenna	Provides an additional 28 dB of gain	Adafruit, New York, NY, USA	14.95
1	IMU	3-axis accelerometer (±2/±4/±8/±16 g); 3-axis magnetometer (±4/±8/±12/±16 gauss); and 3-axis gyroscope (±245/±500/±2000 dps)	Adafruit, New York, NY, USA	14.90
1	Rock7 modem	Input voltage of 5V, data arrives via email, or directly to private web service via HTTP POST	Sparkfun, Boulder, CO, USA	249.95
1	RockBLOCK External Patch Antenna	Frequency range of 1616 - 1626.5 MHz, and bandwidth of 15 MHz	Sparkfun, Boulder, CO, USA	64.95
1	Relay	Non-latching relay, input power of 3.3 V, 250V AC/DC, 1200 W, 10 A	Adafruit, New York, NY, USA	9.95
1	Connection cables	-	-	8.00
1	Portable battery	20100mAh battery		49.99
1	DC-DC converter	Input voltage of 3.2 to 35 VDC, and Output voltage of 1.25 to 30 VDC, maximum output current of 3 A		1.69
	Total			$ 519.33

* Prices retrieved from manufacturers' websites on 28-9-2020.

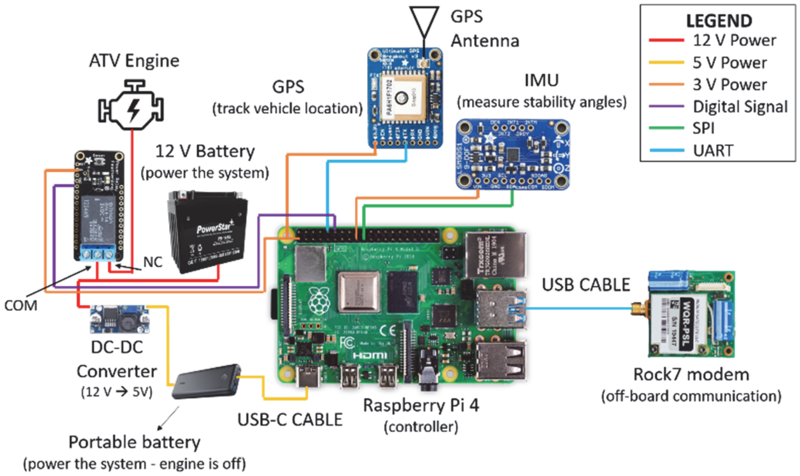


Figure 5. Embedded system mounted on a 2018 Honda Rancher TRX 500 4x4 ATV.

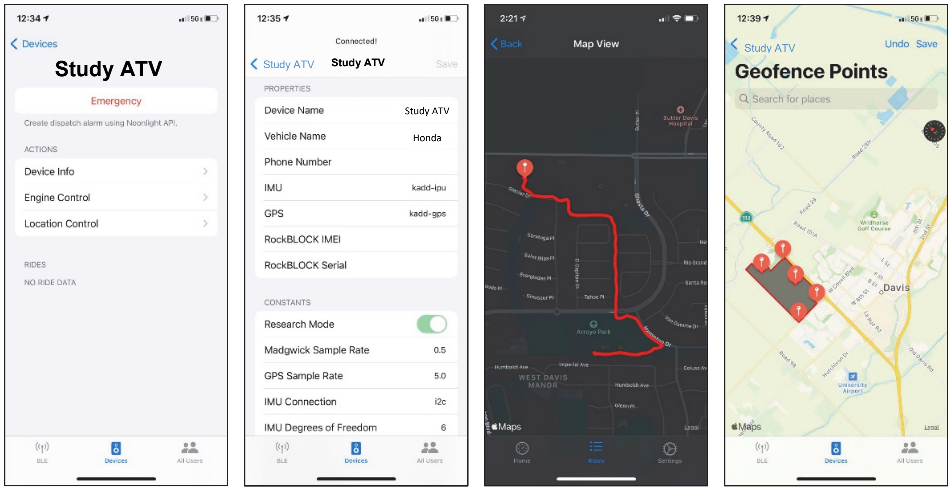
Smartphone Application

The smartphone applications (GP and RP) (fig. 6) were developed using the Swift language, the primary programming language for iOS app development. To enhance the users' experience, customized features and functionality were implemented in the app through CocoaPods, which is a dependency manager for Swift. CocoaPods was built with the Ruby language, which allows packages to be installed and used in the original Swift application. The choice for using iOS smartphones was because it is the most popular choice among users in the U.S., accounting for approximately 50% of smartphone users (Bashir, 2023).

The applications maintain a simple layout that allows users to visualize their past rides. Users can switch between their ATVs via the "Devices menu." When viewing a specific vehicle, all rides are organized by date. As a result, users can view overall ride histories per ride, month, or year. This organizational hierarchy is fully implemented in the application's backend rather than in the remote database. The purpose of implementing this hierarchy in the application's backend is to provide a comfortable and usable experience for users wishing to analyze all collected data. In addition, ATV supervisors can check the performance and riding behavior of their employees. Likewise, parents of young riders can also track their children's performance. With the information supplied by the database, other statistics are calculated and displayed within the application, such as ride times, mileages, and maximum speeds.

Application-Raspberry Pi Communication

One of the main differences between the GP and the RP smartphone applications is their communication with the embedded system. The RP app is meant to be neither used in areas with no cellular service nor monitor the system while the ATV is not in use. For this reason, the communication between the RP app and the RPi only occurs through a proprietary Bluetooth Low-Energy (BLE) communication protocol, which provides fast data access. Data is logged into the remote database when the embedded data logging system is connected to Wi-Fi.



Create dispatch alarm using Noonlight API.

NO RIDE DATA

Device Name Study ATV
Vehicle Name Honda
Phone Number
IMU kadd-ipu
GPS kadd-gps
RockBLOCK IMEI
RockBLOCK Serial

Research Mode ●
Madgwick Sample Rate 0.5
GPS Sample Rate 5.0
IMU Connection i2c
IMU Degrees of Freedom 6

(a) (b) (c) (d)

Figure 6. iOS application interface. (a) Vehicle's menu, (b) Vehicle information, (c) Trip history, and (d) Geo-fencing.

On the other hand, data transmission between the RPi and the GP app only occurs through BLE when the user registers a new ATV into the system. In other cases, the remote database is used as an intermediary between the embedded system and the user (via GP app). In summary, data is transferred from the RPi to the cloud database when a Wi-Fi connection is available, and then the data is shared from the remote database to the user's app.

As mentioned, all the data logged into the embedded system is transferred to the cloud database through Wi-Fi, which inherently requires a Wi-Fi network connection to be established. However, a Wi-Fi network is not necessarily available, especially in remote areas. In order to counteract this drawback, emergency messages are transmitted off-board through the Iridium Satellite Network via the Rock7 modem (available only in the GP app). This modem requires users to pay both an activation fee and a pay-as-you-go rate (€22.0 for a pack of 200 credits) based on the number of bytes sent to the satellite network. Therefore, the RockBLOCK antenna was only used for emergency communication and remote engine shut-off to minimize ongoing costs.

Cloud Database

AgroGuardian's cloud database was developed based on Firebase Firestore, a flexible, scalable database for mobile, web, and server development from Firebase and Google Cloud Platform. It keeps data in sync across client apps through real-time listeners and offers offline support for mobile and web, i.e., AgroGuardian’s iOS application works regardless of network latency or internet connectivity. The riding parameters recorded with the embedded system are sent to the database once the system connects to a Wi-Fi network. These data are then stored in the database and further transferred to the user’s smartphone, which allows users to interpret and interact with their ATV data.

Data Analysis

Rollover Detection System & Geo-Fencing

The performances of the rollover detection and geo-fencing systems were evaluated through a confusion matrix and by the F Score (Wood, 2020), as presented in equation 3.

$$F_{Score} = \frac{TP}{TP + \frac{1}{2}\left(FP + FN\right)} \tag{3}$$

Rollover Report

The system's alert time highly depends on the efficiency of the RockBLOCK antenna to establish a connection with the Iridium Satellite Network and transfer the emergency signal off-board. In the case of an upside-down ATV (the result of a rollover incident), the antenna's efficiency could be compromised since it would not be facing the sky. To optimize the antenna's performance, we tested three design configurations (sensor orientation): antenna facing towards the sky, antenna placed orthogonally (90°), and antenna inverted (upside down). The average alert time of each configuration was compared to each other through an analysis of variance (ANOVA) with a significance coefficient of 5% ($\alpha = 0.05$). Thirty replicates of each design configuration were evaluated. The number of replicates was chosen to ensure a robust statistical analysis in our study while providing a balance between statistical rigor and practical feasibility. Moreover, it is based on standard statistical practices, which suggest that having a sufficiently large sample size increases the power of an ANOVA test, thus ensuring more reliable and generalizable results.

A benchmark of 60 seconds for the EMS notification, as suggested by previous studies (Champion et al., 2003; Funke et al., 2000), was adopted as the desired outcome of the system. The design configuration with the shortest alert time was compared to the benchmark by a t-test with a significance coefficient of 5% ($\alpha = 0.05$).

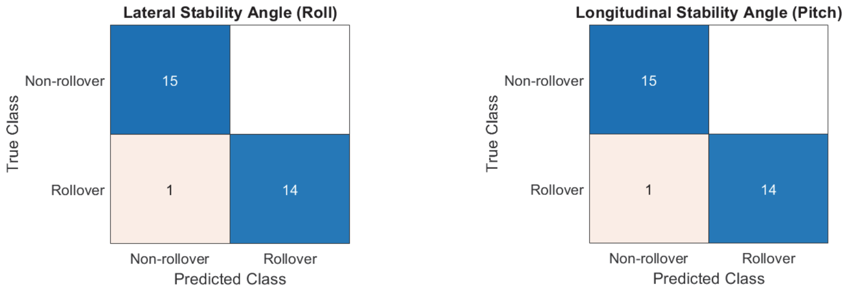
Vehicle Tracking

The performance of the vehicle tracking system was evaluated separately for both position and velocity estimates. The response variables were the average position deviation and the average velocity error. Critical values were set as 10 m (position) and 1.0 m s^{-1} (velocity). Although the desired outcomes may seem well below the accuracy delivered by state-of-the-art GPS devices/tracking algorithms, very high accuracy is not critical for the success of this system. For instance, personal locator beacons (PLBs), which have an accuracy of about 100 m when interfaced with GPS, have been used successfully to aid EMS responders in locating ATV crash patients and stranded mount hikers (Maritime New Zealand, 2018; Mountain Gear and ACR Electronics, 2007; BusinessWire, 2008; The Gisborne Herald, 2017; Wubben et al., 2019). In addition, a benchmark of 100 m, 67% of the time, was previously proposed by Funke et al. (2000) when evaluating the accuracy of automated collision notification systems (ACNs) for automobiles. The null hypotheses ($\overline{D} \leq 10$ m; $\overline{V}_{error} \leq 1.0$ m s^{-1}) were tested through a t-test with a significance coefficient of 5% ($\alpha = 0.05$).

Results and Discussion

Rollover Detection

A confusion matrix was computed and plotted for both lateral and longitudinal stability angles (fig. 7). In each matrix, the detection of a rollover event is labeled in both the horizontal and vertical axes. The horizontal axis represents the number of incidents predicted in each class (rollover / non-rollover) by the system, and the vertical axis represents the ground truth data. True negative cases occur when the true class is “non-rollover” and the predicted class is also “non-rollover” (upper left corner of the matrix). Similarly, false positive cases occur when the true class is “non-rollover,” but the predicted class is “rollover” (upper right corner of the matrix); false negative cases occur when the true class is “rollover,” but the predicted class is “non-rollover” (lower left corner of the matrix). Lastly, true positive cases occur when the true class is “rollover” and the predicted class is also “rollover” (lower right corner of the matrix).



(a) **(b)**

Figure 7. Rollover detection system performance.

The accuracy of the incident detection system is crucial because the outcomes of a misclassification come at an expensive cost. For instance, a false positive outcome would trigger EMS and lead them to a location where there is no crash. On the other hand, a false negative outcome is more critical because it implies that first aid will not be rendered when it is needed the most.

AgroGuardian presented identical results for both lateral rollover and longitudinal rollover detection, highlighting its robustness. In addition, the overall accuracies of 0.96 and F-scores of 0.96, which are higher than the rollover accuracy reported by Funke et al. (2000) (93%), indicate that the system was very effective in distinguishing rollover from non-rollover incidents.

A deep analysis of the data revealed that the system presented an angle estimate error of 0.8 ± 0.15° (95% Confidence Interval – CI). Since rollover detection is a binary variable, it is reasonable to conclude that the system will only fail when the ATV is ridden at slopes within 0.95° of their rollover thresholds. For example, assuming that the lateral rollover threshold of our study ATV (2018 Honda Rancher TRX 500 4x4) is 44.6° (Grzebieta et al., 2015c), the system will only fail if the ATV is operated on slopes between 43.65° and 45.55°. Indeed, in our trials, the system only failed when the sensor was tilted at 45° (lateral rollover tests). Similarly, for tests of longitudinal rollover, the system only failed when the sensor was tilted at an angle of 28.1° (the study ATV's longitudinal rollover threshold is 27.6°).

Due to the technical difficulties of conducting a rollover simulation (e.g., damage to the vehicle’s frame or sensing equipment, a sufficient number of replicates, etc.), we set up a bench test that included very specific tilting angles, such as those that are close to the ATV rollover thresholds. However, in a real-life scenario, riders are extremely unlikely to operate the ATV at angles close to the ATV thresholds. That is either because riders are afraid of riding at steep slopes (Cavallo et al., 2015) or because the ATV will simply roll over when it is tilted beyond its stability angle. Thus, we conclude that AgroGuardian is unlikely to miss a rollover in real riding conditions.

Crash Report System

The total alert time of three key emergency signals was evaluated, including (I) rollover detection, (II) emergency notification receiving in AgroGuardian's web server, and (III) *Noonlight* confirmation of an emergency alert. The time elapsed between (I) and (II) indicates the RockBLOCK antenna’s capability to connect to the Iridium Satellite Network. The time elapsed between (II) and (III) only depends on internet speed. For this reason, we assessed the system's alert time through three metrics: (a) the time from (I) to (II), defined as off-board communication time; (b) the time from (II) to (III), defined as internet time; and (c) the total time, calculated as the difference between (III) and (I).

An initial attempt at collecting the data consisted of placing the RockBLOCK antenna directly on top of the ATV handlebar (the tallest point of the ATV). However, it was observed that the antenna would always fail to send off-board messages when its antenna was placed upside-down (inverted), directly touching the ground without any gap. In order to fix this issue, we placed the sensor on the ATV chassis, which was located at a height of approximately 0.25 m (10 in.) below the handlebar. This new configuration created a clearance zone between the antenna and the ground when the ATV was upside-down. The remaining tests were performed with the new configuration for the antenna. The average alert times of each treatment are presented in table 2.

Table 2. Comparison of AgroGuardian's alert time intervals in seconds for different sensor orientations.

	Sensor Orientation	Range (s)	Average (SD)[a],[b] (s)	CV[c] (%)	p-value[d]
Off-board communication time[e]	Upright	14-190	35.60 (42.46)	119.26%	0.357
	Orthogonal (90°)	9-354	40.60 (66.86)	164.7%	
	Inverted	8-82	23.57 (18.60)	78.9%	
Internet time[f]	Upright	3-12	5.10 (1.84)	36.2%	0.366
	Orthogonal (90°)	2-46	7.77 (9.12)	117.5%	
	Inverted	3-48	6.93 (8.84)	127.6%	
Total time	Upright	18-196	40.70 (42.61)	104.7%	0.364
	Orthogonal (90°)	12-360	48.37 (68.14)	140.9%	
	Inverted	11-108	30.60 (23.15)	75.7%	

[a] SD = standard deviation.

[b] Sample size (n) = 30.

[c] CV = coefficient of variation.

[d] F-test for comparison of means through ANOVA.

[e] Off-board communication time = time elapsed between rollover detection and emergency notification receiving in AgroGuardian's web server.

[f] Internet time = time elapsed between emergency notification receiving in AgroGuardian's web and server *Noonlight* confirmation of emergency alert.

As expected, the internet time is independent of the sensor orientation (p-value = 0.366). Furthermore, no specific sensor orientation yielded a significantly smaller alert time for off-board communication (p-value = 0.357) or for the total time (p-value = 0.364). This is an important finding, as it leads to the conclusion that the system works even when the ATV is upside-down. Results demonstrated that RockBLOCK can connect to the Iridium Satellite Network as long as there is a clearance zone of at least 0.25 m above its antenna, which is about the height difference between the study's ATV handlebars and chassis.

It is important to mention that smaller ATV models, such as youth models, might have a different clearance zone between the chassis and the handlebars. For those cases, the validity of our results might be questionable, and more research would be needed. Nevertheless, the ATV evaluated (2018 Honda Rancher TRX 500 4x4) is representative of an average adult-sized ATV commonly used among riders on farms and ranches in the U.S.

Emergency medical service (EMS) alert time intervals for ATV crashes likely have a critical impact on patient health (e.g., chances of survival, injury severity, and hospital length of stay) (Wubben et al., 2019). For instance, a previous study about car incidents reported that riders are three times more likely to survive a crash if EMS is notified within 60 seconds (Champion et al., 2003). Therefore, it is essential to minimize the EMS alert time to an incident. The national U.S. average elapsed time between crashes and EMS notification is 228 seconds for urban crashes and 408 seconds for crashes in rural areas (Champion et al., 2003). The results of the t-test confirmed that AgroGuardian's alert time (95% CI = 40.70 ± 13.17 seconds) is significantly shorter than the benchmark of 60 seconds (Funke et al., 2000) (p-value < 0.001) and about ten times faster than the national average for rural areas.

Vehicle Tracking System

The performance of AgroGuardian's tracking system is presented in a graph (fig. 8) that compares the vehicle's location measured by AgroGuardian and the RTK GPS. Since the collected data was converted into UTM coordinates, the x and y values of those coordinates become inherently large (e.g., x = -548,749.30; y = 4,176,423.74), which hinders the visualization of the data. In order to enhance the quality of figure 8, the coordinate points (x_i, y_i) from the experimental trials were converted from "world frame" (i.e., original UTM coordinates) to “local frame” by subtracting the origin (x_0, y_0) from the rest of the samples. It is important to highlight that the same origin was used for both datasets (AgroGuardian and RTK receiver). In other words, the data was processed according to equations 4-7:

$$x_{agro} = x_{agro} - x_{RTK\ 0} \tag{4}$$

$$y_{agro} = y_{agro} - y_{RTK\ 0} \tag{5}$$

$$x_{RTK} = x_{RTK} - x_{RTK\ 0} \tag{6}$$

$$y_{RTK} = y_{RTK} - y_{RTK\ 0} \tag{7}$$

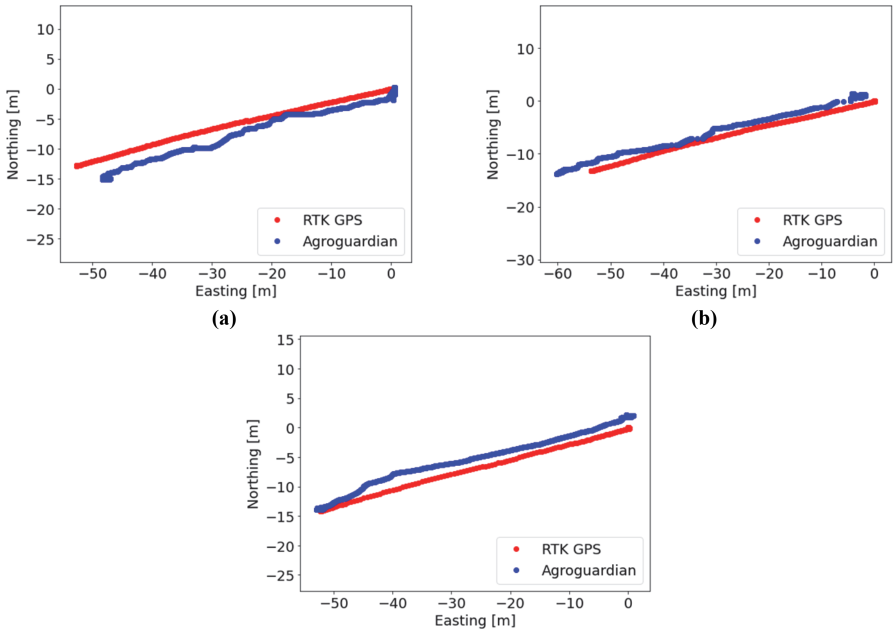
A summary of the performance of AgroGuardian’s tracking system is presented in table 3 and figure 8. The sample size, mean, standard deviation, and confidence interval for position deviation for the GPS module were 29,013, 2.34, 2.01, and 2.32-2.36 m, respectively (table 3). Using a similar low-cost GNSS module, Silva et al. (2019) obtained average deviations of 2.37 and 3.32 m in dynamic tests with velocities of 2.22 and 4.17 m s^{-1}, respectively.

Table 3. Descriptive statistics for AgroGuardian’s position estimate error (m).

Test Velocity (m s^{-1})	Range (m)	Average (SD)[a] (m)	CV[b] (%)
2.23	0 - 8.53	3.22 (2.14)	67%
3.57	0 - 10.24	2.17 (1.88)	86%
5.36	0 - 12.13	1.67 (1.67)	100%
Total	0 - 12.13	2.34 (2.01)	86%

[a] SD = standard deviation.

[b] CV = coefficient of variation.



(a) **(b)**

(c)

Figure 8. AgroGuardian’s localization performance tests for several speeds. (a) Test at 2.23 m s^{-1} (5 mph), (b) test at 3.57 m s^{-1} (8 mph), and (c) test at 5.36 m s^{-1} (12 mph).

It is noteworthy that AgroGuardian’s accuracy is greater than that of PLBs, which served as a baseline for comparison. Moreover, the result from the t-test showed that the average position deviation of AgroGuardian’s vehicle tracking system (95% CI = 2.34 ± 0.02 m) was significantly smaller than 10 m (p-value < 0.001), concluding our null hypothesis.

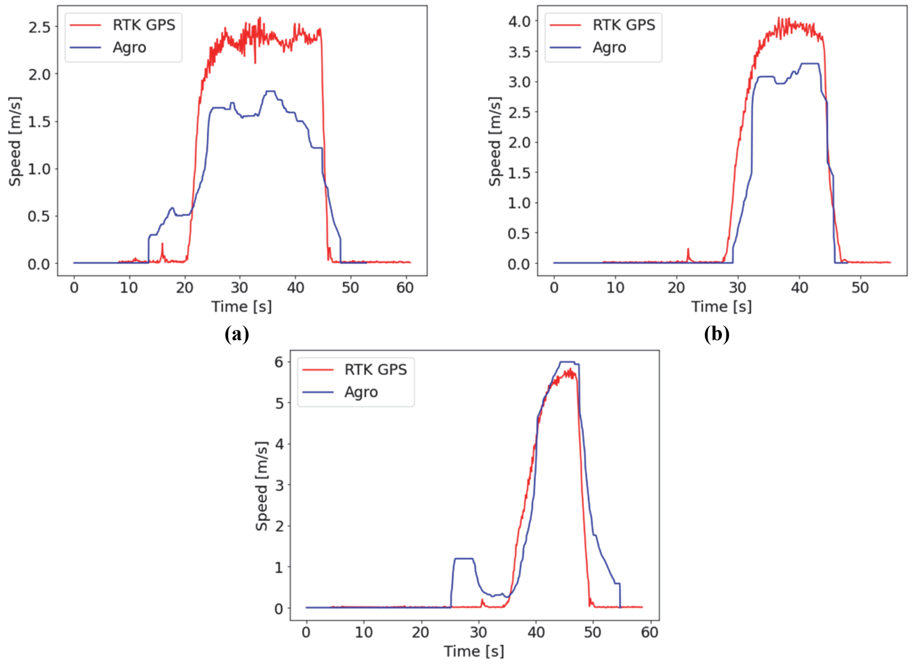
A summary of the performance of AgroGuardian’s speed tracking system is presented in table 4 and figure 9. The average velocity error for the speeds of 2.23, 3.57, and 5.36 m s^{-1} were 0.77, 0.63, and 0.88 m s^{-1}, respectively (table 4). Moreover, the average error across all replicates was 0.75 ± 0.02 m s^{-1} (95% CI). These values are significantly smaller than our selected benchmark of 1.00 m s^{-1} (p-value < 0.001). Despite the lower precision compared to state-of-the-art tracking devices, it is possible to use AgroGuardian’s low-cost system to track the riding parameters (position and velocity) with reasonable accuracy.

Table 4. Descriptive statistics for AgroGuardian’s velocity estimate error (m s^{-1}).

Test Velocity (m s^{-1})	Range	Average (SD)[a]	CV[b] (%)
2.23	0 - 2.72	0.77 (0.88)	114%
3.57	0 - 3.97	0.63 (0.97)	152%
5.36	0 - 4.89	0.88 (0.99)	112%
Total	0 - 4.89	0.75 (0.95)	126%

[a] SD = standard deviation.

[b] CV = coefficient of variation.



(a)

(b)

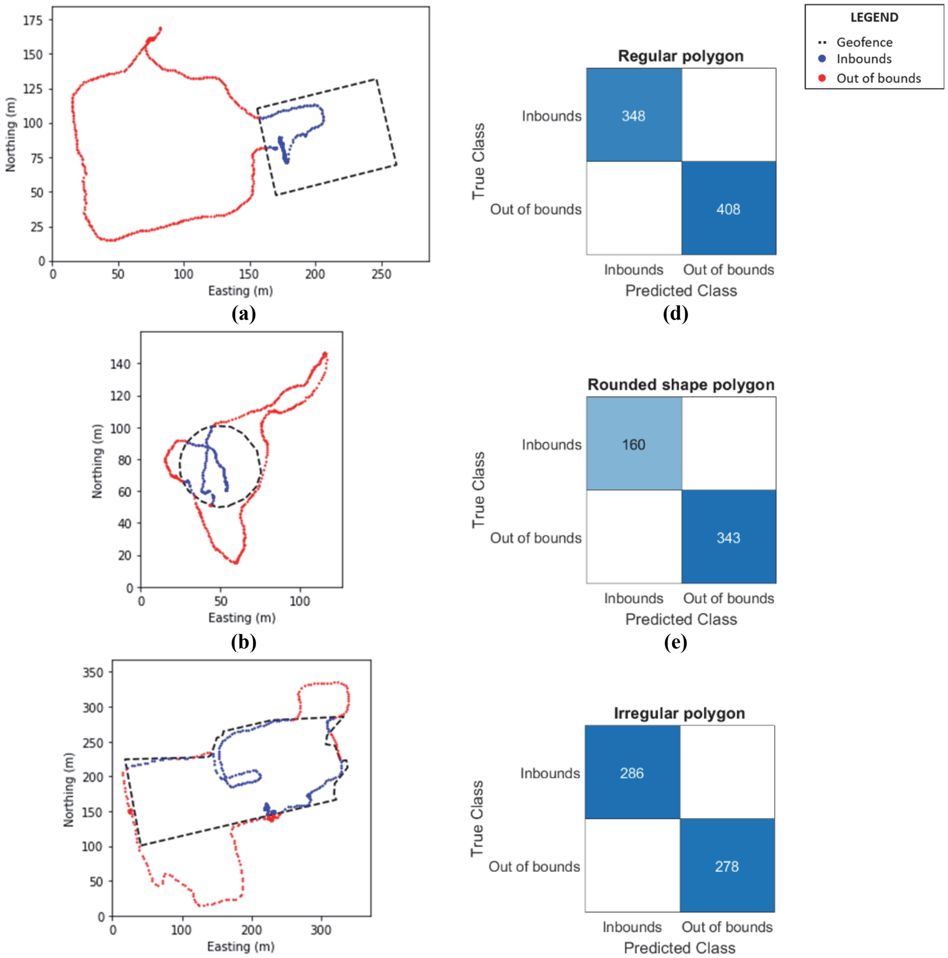
(c)

Figure 9. AgroGuardian’s velocity performance tests for several speeds. (a) Test at 2.23 m s^{-1} (5 mph), (b) test at 3.57 m s^{-1} (8 mph), and (c) test at 5.36 m s^{-1} (12 mph).

Geo-Fencing

A summary of the performance of AgroGuardian's geo-fencing is presented in figure 10. AgroGuardian presented perfect accuracy (100%) for detecting points inbounds and out-of-bounds, as seen in the maps and the confusion matrices, with an F-Score of 1.0 for all tests. Furthermore, the results indicated that the system's accuracy is independent of the geo-fence shape since all tests yielded the same results.

As previously discussed, geo-fencing is a practical application that increases the rider's safety as well as the asset's safety. The accuracy achieved in the field trials reinforces AgroGuardian's capability to improve ATV riders' safety.



(a) (d)

(b) (e)

(c) (f)

Figure 10. Geo-fencing performance assessment. (a) Test for regular polygon; (b) Test for rounded shape polygon; (c) Test for irregular polygon; (d), (e), (f) Confusion matrices of (a), (b), and (c), respectively.

Discussion

A staggering number of riders die or sustain severe injuries every year due to ATV-related incidents. The full extent of the geographic patterns of those injuries and deaths is yet unknown. However, compelling evidence suggests that riders injured in isolated or small rural areas suffer a disproportionately higher mortality rate relative to their counterparts in more urban areas (Qin et al., 2016, 2017). That is even though riders injured in off-road crashes are more likely to be helmeted and less likely to be intoxicated or carry additional passengers (Denning et al., 2013a; Denning et al., 2013b; Lin and Blessing, 2018). The higher fatality rates in more rural and remote areas may be partially explained by longer EMS patient access and transfer times. On average, first aid rendering times are 38% longer for crashes in remote locations versus accessible locations, disregarding the time interval from crash to EMS notification (Wubben et al., 2019).

A possible short-term solution for the alarming rates of ATV-related fatalities and severe injuries, particularly in isolated or rural areas, relies on the use of crash detection devices that can rapidly alert EMS and emergency contacts. In the present manuscript, we developed and validated a system (AgroGuardian) that automatically detects the occurrence of rollovers and notifies EMS in less than a minute. Performance tests indicated that AgroGuardian's time to notify *Noonlight* was on average 40.70 seconds, and its crash localization feature presented an accuracy of 2.34 m. Based on the GPS coordinates provided to *Noonlight*, the estimated EMS arrival time at the crash site was approximately 8 minutes. Moreover, it presented an overall accuracy of 0.96 for rollover detection. Such a system can not only facilitate swifter medical interventions but also bridge the critical time gap, potentially mitigating the severity of injuries.

Different approaches could be considered to improve the system's performance. The use of machine learning algorithms could enable the system to analyze possible non-linear patterns to anticipate potential rollovers. It could be beneficial, especially, to improve the system's accuracy in different types of environments and scenarios (e.g., type of terrain, weather conditions, etc.). Further, different methods or components could be considered as a way to decrease EMS notification time. Several factors, including a delay in the call center's response, could increase the system's time to notify *Noonlight*, thus increasing EMS notification time.

Conclusions

In this study, we developed and evaluated the performance of an automatic ATV rollover detection and notification device. AgroGuardian can accurately detect a rollover. It proved to be very effective in distinguishing rollover from non-rollover incidents with 96% accuracy. The device presented a fast EMS notification time (40.7 seconds) when compared to the benchmark of 60 seconds as suggested by previous studies. Moreover, the ATV localization system presented an average error of 2.34 m. Lastly, the remotely controlled shut-off system, anti-robbery, and geo-fencing systems are functional, and work based on adjusted values.

Acknowledgments

This work was supported by the University of California, Davis [grant number #4659] and the Western Center for Agricultural Health and Safety/NIOSH [grant number #U54OH007550].

The authors would like to acknowledge the support provided by Davy Chuon and Kaito Yoshida of the Department of Computer Science for their assistance at the initial stage of this study.

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