Monitoring coastal aquaculture devices in Taiwan with the radio frequency identification combination system

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ABSTRACT
Marine debris significantly influences the environment and economics of marine ecosystems. Measures to ban illegally discarded materials using monitoring techniques are expected to mitigate marine debris mismanagement. For example, derelict oyster farming rafts along the southwestern coast of Taiwan have been a source of marine debris pollution since the 1980s. An efficient inspection system is an urgent requirement for monitoring oyster farming areas and is expected to implement control and surveillance measures for litter discarded from coastal fisheries. To address this issue, this study examined combinations of radio frequency identification (RFID), drone archiving, and onshore receiving systems to ascertain the positions of oyster rafts and their owners with digitally tagged labels. The results showed that the two proposed monitoring systems are feasible for use in marine environments. The RFID signals archived by the drone reached 100% of the 200 tags with a spatial bias ranging from 2.38 to 59.99 m. RFID-GPS hybrid tag signals received by the onshore station covered 100% of the 20 tags with spatial bias ranging from 1.27 to 10.47 m. The RFID-GPS hybrid system was confirmed as a feasible approach for monitoring oyster rafts within 3 km of the coast. The real-time (1 h intervals) position and attributes of each raft detected by the system indicated that our designed techniques enhance responsible fishery surveillance and management of coastal aquaculture worldwide.

1. Introduction
Oyster farming fisheries are the most traditional form of aquaculture along the western coast of Taiwan. Major oyster farming areas are located on the coasts of the Hsinchu, Changhua, Yunlin, Chiayi counties, and Tainan City (Liu, Kao, and Chen 2015). Oyster farming methods used in Taiwan include bamboo rafts, hanging, suspension, and long-line methods, and the floating raft culture method, which is the most widely used method on the western coast. The approximately ten thousand floating rafts per year account for the largest concentration in Taiwan (National Audit Office Taiwan 2015). (Figure 1). However, four to seven typhoons affect Taiwan annually, and the extreme storm surges and heavy rain lead to aquaculture infrastructure damage. Consequently, torn oyster farming rafts are widely scattered by currents and become derelict fishing gear that presents a serious marine pollution problem. Derelict gear is produced by natural disasters and arbitrarily discarded by fishermen after oyster harvests (Liu, Kao, and Chen 2015). In response, the oyster farming management regulations promulgated by the Tainan City government in 2012 restricted the oyster farming season from October 1st to June 30th. The regulations further stipulate that: fishermen must register the number of rafts deployed at sea; floating facilities must be marked with special flags for identification, and fishermen must then return the registered farming rafts at the end of the harvest season; fishermen who deliberately discard rafts will be fined at approximately USD 100 per raft. Unfortunately, non-compliant fishermen have frustrated government officers due to weak law enforcement for monitoring unreported oyster rafts at sea. Thus, derelict rafts and enclosed Styrofoam pieces continue to damage and pollute coastal areas. To resolve this problem, the Tainan City government seeks a highly accurate and efficient monitoring system to supervise the position of oyster farming rafts.

Chen, Chang, and Shih (2010) used Formosa 2 satellite imagery and Geographic Information Systems (GIS) software to detect oyster rafts off the
Tainan coast and identified 98.4% of the total rafts. Yang et al. (2018) proposed a classification method to extract oyster farming raft data from unmanned aerial vehicle (UAV) images, a method that provides a quantitative assessment by efficiently identifying oyster farming rafts from UAV images. Moreover, previous studies have developed methods for extracting marine aquaculture foundations from satellite images and have identified the exact location of aquaculture facilities, such as offshore rafts and aquaculture cages (Liu et al. 2020; Murata et al. 2021; Wang et al. 2019, 2017; Zhang et al. 2020). However, the methods in the above-mentioned studies only identified the number and position of registered oyster farming rafts and could not identify farmers or the registration status of their oyster farms.

Marine debris monitoring systems are needed for marine pollution management; for example, the US government emphasized the need to consistently monitor and identify marine debris sources to help implement effective control measures for pollution source reduction (U.S. Commission on Ocean Policy 2004). The Food and Agriculture Organization of the United Nations (UNFAO) proposed fishery monitoring, control, and surveillance (MCS) to achieve sustainable and responsible fishery management. The MCS represents a crucial executive approach for enhancing coastal fishery management. The establishment of the MCS system and the need for applied research are vital for sustainable and responsible fishery management (Flewwelling et al. 2003).

RFID systems are touchless communication devices with automatic identification and data collection (AIDC) technology that are used to automatically identify and track tags attached to objects. The RFID system consists of two principal components: a transponder or tag and an interrogator or reader. Moreover, transponders are classified as active or passive based on the power source requirements (Finkenzeller 2010). Three RFID transmission frequencies have been used worldwide. Low-frequency (LF) RFID systems commonly operate within a frequency range of 100–135 kHz (typically 125 kHz). High-frequency (HF) RFID systems operate at 13.56 MHz. Ultra-high frequency (UHF) RFID systems typically operate in the frequency range of 860 MHz–960 MHz, as well as selected frequencies of 433 MHz, 2.45 GHz and 5 GHz, depending on the RFID application requirements (Jankowski-Mihułowicz and Definition 2017). Based on international frequency regulations, 433 MHz offers the widest acceptance for active RFID (Seetharam and Fletcher 2007; Savi Technologies 2007) and is effective for asset tracking and management systems (Kadir, Evizal, and Rahim 2013). Furthermore, the 433 MHz frequency has fewer problems with metals and liquids than higher frequencies, and the communication range is greater than that of LF and HF RFID systems (Ruiz-Garcia and Lunadei 2011). To achieve long ranges and stable readings, an active transponder with an operating frequency of 433 MHz was used in this study.

RFID technology can be applied in various areas, such as data transfer, location identification, supply chain management, security, asset tracking, and access control (Kaur et al. 2011). Moreover, previous studies have indicated that RFID technology has been employed in fishery monitoring systems for data acquisition, localization, and automatic monitoring (Bennett et al. 2016; Miyamoto et al. 2006). RFID also contributes to the fight against illegal, unreported, and unregulated (IUU) fishing and reduces the amount of abandoned, lost, or discarded fishing gear (ALDFG) (He and
Suuronen 2018). La Velley, Brickett, and Moffat (2010) presented an innovative automatic RFID and global positioning system (GPS) system to monitor fishing gear that provides line identification, real-time fixed gear, and fishing monitoring. BIM (2007) tested RFID systems to evaluate a variety of marker buoy approaches to mark fishing gear to combat IUU fishing. The report addressing the RFID system could be a useful technique for buoy location under disadvantageous conditions. Uchida et al. (2005) developed an automatic monitoring system that combines RFID and GPS to monitor conger-eel fishing. A prototype system was successfully employed to record individual conger-eel tube locations and catch times.

In this study, two experimental monitoring systems were proposed to identify the position of oyster farming rafts in real time using the RFID-drone and RFID-GPS hybrid systems. GIS software was employed to map the positions of the oyster farming rafts in real time using monitoring data and satellite images. The study objectives were to evaluate the readability of RFID tags in receiving distance from the coast, reliable displacement bias, and receiving frequency in the farming season (October to June) as high as the battery power supply.

![Figure 2. Block diagram of RFID-drone system.](image)

2. Materials and methods

2.1. RFID-drone system

The RFID-drone system combines the mobility of a multicopter with wireless sensors and can be applied in several fields, such as environmental monitoring (Allegretti and Bertoldo 2015; Greco et al. 2015), inventory management (Bae et al. 2016), accident or disaster scenarios (Leizer, Károly, and Tokody 2017), material tracking (Hubbard et al. 2015), and the Internet of Things (IoT) industry (Fotouhi, Ding, and Hassan 2017). The RFID-drone system is also used for localization (Jasrotia and Nene 2019) in construction (Won, Chi, and Park 2020) and inventory management (Li et al. 2021).

The proposed RFID-drone system in this study consists of two components: (1) the RFID-mounted drone and (2) the active RFID tags. Figure 2 shows a diagram of the RFID-drone system components. The RFID system performance is limited by the RFID tag collision problem, which causes the reader to receive collided signals and is unable to identify RFID tags rapidly and correctly when implemented with multiple tags (Finkenzeller 2010). Thus, the RFID reader used in the present study has a built-in processor for data acquisition and the ability to read multiple RFID tags (anti-collision capability). Active RFID tags were used in this study to obtain long-range readings. An active RFID tag has a transmitter and an on-board power supply (typically a battery). The electric power of the RFID reader is provided by a tablet and operates at a frequency of 433.96 MHz. Communication was maintained through a serial port with a high baud rate of 115,200 b/s. Moreover, the reading distance reached 50 m through an external high-gain 8 dBi omnidirectional antenna. An antenna is a device that couples guided electromagnetic waves into free-space electromagnetic waves to enable wireless communication in an RFID system (Karmakar 2010).

A single-rotor drone was used for the experiment. The hover time of the drone was 40 min, and the maximum takeoff weight was 12 kg. The operating frequency of the drone (2.4 GHz) was outside the frequency range of the RFID reader, which was connected (along with a GPS receiver, and RFID antenna) to a tablet with a USB communication protocol (Figure 3) and equipped to a drone (Figure 3). Since the RFID tags were fixed on the oyster farming rafts (Figure 3), an off-the-shelf plastic waterproof case was used to enclose the RFID tags (Figure 3), which were battery-powered.
and contained an antenna that enabled signal transmission. Table 1 lists the specifications of the RFID reader, RFID tag, and GPS receiver. To receive the RFID signal, the researcher operated a drone in the autopilot route to collect data from the RFID tags that were fixed on the bamboo pole of each oyster farming raft. The RFID reader simultaneously receives signals from the RFID tags and the GPS receiver. The data thus collected included the RFID ID number, latitude, and longitude, and were saved in a comma-separated values (CSV) file and stored in the tablet for further analysis. Table 2 lists the cost of each RFID tag placed on the raft.

### 2.2. RFID-GPS hybrid system

The development of an integrated RFID-GPS system has been partially successful in certain fields. For example, Poaad and Ismail (2015) designed and developed an RFID system by combining 2.45 GHz active RFID, GPS, and a global system for mobile (GSM) technologies to extend the abilities of the standard RFID. The integrated system on the device applies a wireless sensor network (WSN) platform with an automated switching algorithm to track objects in different environments within a control or global area. Li et al. (2010) developed a hybrid RFID-GPS-based terminal system that permitted real-time transportation and improved the accuracy and efficiency of digital logistics transportation management. Moreover, Hutabarat et al. (2016) designed and developed a human tracking system by combining RFID and GPS technologies to track targets in both indoor and outdoor areas. Moreover, Wilson Cheruiyot,

![Figure 3](image-url)

**Figure 3.** RFID-drone system. (a) Equipment layout for an active RFID system. (b) The RFID reader, GPS receiver, RFID antenna, and a tablet mounted on a drone. (c) The RFID tags fixed to the bamboo pole on the oyster farming rafts. (d) The proposed RFID tag that is battery powered to send the signal automatically.

| **Item** | **Quantity** | **Prices $ (USD)/pc** |
|----------|--------------|-----------------------|
| RFID tag | 1            | 30.68                 |
| Fixing device | 1          | 5.41                  |
| Total    | 1            | 36.09                 |

#### Table 2. Cost of each RFID tag placed on the raft.

| **Item**              | **Quantity** | **Prices $ (USD)/pc** |
|-----------------------|--------------|-----------------------|
| RFID reader           |              |                       |
| Frequency: 433.96 MHz |              |                       |
| Signal strength: 10 dBm |             |                       |
| Power Supply: 3 V     |              |                       |
| Transfer Rate: 128 kbps |           |                       |
| RFID tag              |              |                       |
| Frequency: 433.96 MHz |              |                       |
| Signal strength: 10 dBm |             |                       |
| Power Supply: 3 V     |              |                       |
| Operating current: 18 mA |           |                       |
| GPS receiver          |              |                       |
| Frequency: L1, 1575.42 MHz |       |                       |
| Sensitivity: −163 dBm |              |                       |
| Channels: 48          |              |                       |
| Accuracy: <2.5 m      |              |                       |
| 2D RMS SBAS Enable    |              |                       |

**Table 1.** Specifications of RFID reader, RFID tag, and GPS receiver.
Okeyo, and Ochieng (2021) designed a framework and proposed an alert system that combines RFID, GPS technology, and location-based services (LBS) to relay information to car drivers to prevent road accidents at black spots.

The RFID-GPS hybrid system proposed in this study consists of two components: (1) an RFID signal receiving station and (2) an RFID-GPS hybrid tag. The RFID signal receiving station consists of an RFID reader, a directional antenna, a USB-RS485 cable, and a personal computer (PC). The RFID-GPS hybrid system (Figure 4) is characterized by GPS chips embedded in RFID tags, while the tag position can be directly received by the reader at the ground station. A signal amplifier module is also inserted to generate radio frequency (RF) power and achieve better signal strength and transmission distance. The GPS module is a GPS signal-receiving module that obtains the necessary positioning and navigation information (Rahiman and Zainal 2013). The RFID-GPS hybrid tag was equipped with a u-blox MAX-8 global navigation satellite system (GNSS) receiving module that has a position accuracy of 2.5 m CEP for GPS and 4.0 m CEP for GLONASS.

An RFID reader with a directional antenna was installed on top of a building (Figure 5) and connected to a PC through a USB-RS485 cable (Figure 5). The RFID reader used in this system was the same as that used in the RFID-drone system. The RFID-GPS hybrid tag consists of an RFID tag module, a GPS chip, a GPS antenna, and an omnidirectional antenna (Figure 5). Since the RFID-GPS hybrid tag was fixed on the oyster farming rafts in a marine environment (Figure 5), a waterproof box (IPX8) was used to encase the RFID-GPS hybrid tag. Table 3 lists the specifications of the GPS and signal amplifier modules. To conserve battery life, the RFID-GPS hybrid tag switched to dormant mode after signal transmission. Furthermore, the positional and relative data of the RFID-GPS hybrid tag were periodically transmitted. When the RFID reader receives the signal, the data collected from RFID tag readings (e.g., the RFID ID number, latitude, longitude, battery level, and received signal strength indicator (RSSI) values) were saved in a CSV format file by using the Auto-Save feature. Table 4 lists the cost of each RFID-GPS hybrid tag placed on the raft.

### 2.3. Floating oyster rafts detection from satellite

Satellite imagery analysis is a promising method for monitoring oyster farming in China (Zhang et al. 2020). For the detection of floating oyster rafts, the near-infrared (NIR) bands of a SPOT-7 (Satellite Pour l’Observation de la Terre) satellite were used to analyze the position of oyster farming rafts. Table 5 lists the specifications of the SPOT-7 satellite sensor. Water bodies appear dark in the images due to their strong absorbance and low reflectance at NIR wavelengths. Areas devoid of water bodies appear brighter owing to high reflectance (Haibo et al. 2011; Mondejar and Tongco 2019; Oliveira, Kampel, and Amaral 2008). NIR imaging has been widely used for various applications in the marine environment and is useful for water body location and delineation (Mondejar and Tongco 2019), geomorphological observations (Oliveira, Kampel, and Amaral 2008), marine sediment determination (Chang et al. 2005), shoreline (van der Werff 2019) and coastal wetland biomass mapping (Doughty and Cavanaugh 2019), and information provision for flooded areas (Ban et al. 2017).

The satellite image was pre-processed before the detection experiment by image clipping to focus on the target area for subsequent image analysis. The experimental environment CPU was an Intel (R) Core
The satellite images were analyzed using ArcGIS software (v10.5). Figure 6 presents a flowchart of the image-analysis procedure. For oyster raft detection, the NIR satellite image was classified using the Iso Cluster Unsupervised Classification tool in ArcGIS, which identifies the number of spectral classes or clusters in the image without researcher intervention (Step 2). Step 3 (the reclassification process) divides the complete value range into several classes; the newly assigned values are reclassified to identify oyster farming rafts. The classes of all water bodies were set to “NoData” and grouped with the reclassified raster layers, which represent the oyster farming rafts within a single given class. The ArcGIS Raster to Polygon tool was used to convert the raster dataset

### Table 3. Specifications of GPS and signal amplifier modules.

| Product variants: u-blox MAX-8 C | Frequency Band: 400 MHz-480 MHz |
| Receiver type: 72-channel u-blox 8 engine | Receiving Noise Figure: ≤2.5 dB |
| Nav. update rate: Up to 18 Hz | Transmitting Gain: 10 dB-20 dB (±2 dB) |
| Position accuracy: GPS 2.5 m CEP, GLONASS 4 m CEP | Maximum Transmitting Power: 33 dBm (2 W) |
| Sensitivity: Tracking –166 dBm |

### Table 4. Cost of each RFID-GPS hybrid tag placed on the raft.

| Item          | Quantity | Prices $ (USD)/pc |
|---------------|----------|-------------------|
| RFID tag      | 1        | 90.24             |
| Fixing device | 1        | 5.41              |
| Total         | 1        | 95.65             |

### Table 5. SPOT-7 Satellite sensor specifications.

| Specification                          | Description                                      |
|----------------------------------------|--------------------------------------------------|
| Launch date                            | 30 June 2014                                     |
| Multispectral Imagery                 | Blue (0.465 µm – 0.525 µm)                        |
|                                       | Green (0.530 µm – 0.590 µm)                       |
|                                       | Red (0.625 µm – 0.695 µm)                        |
|                                       | Near-Ir. (0.760 µm – 0.890 µm)                    |
| Resolution (GSD)                      | Panchromatic – 1.5 m                             |
|                                       | Multispectral – 6.0 m (B,G,R,NIR)                 |
| Location accuracy                      | 10 m (CE90)                                      |
| Imaging swath                          | 60 km at Nadir                                   |
| Revisit                                | 1 day with SPOT 6 and SPOT 7 operating simultaneously |
|                                       | Between 1 and 3 days with only one satellite in operation |
Figure 6. Steps of oyster farming raft detection experiment using GIS and satellite imagery.

into polygon features (Step 4), and the ArcGIS Smooth Polygon tool was used to smooth the sharp angles in the polygon outlines (Step 5). The ArcGIS Centroids tool was employed to generate a point feature at the centroid of the polygon feature data (green points in Step 6), and the point features obtained from the RFID tags were imported and compared (red points in Step 6). Finally, the ArcGIS Near tool was used to calculate the distance from each point feature to the nearest target feature point to identify the oyster farming rafts.

3. Results

3.1. Spatial bias of the RFID-drone system

The RFID-drone system experiment was conducted on June 2019, and the RFID system and GPS receiver had an overall weight of 1 kg and were mounted on a drone. A ground control station (GCS) was equipped with a laptop, telemetry radio antenna, and autopilot software (Mission Planner) (Figure 7). The drone flew autonomously to acquire the flight parameters (e.g. altitude, airspeed, heading, and current position) in real time. The drone covered the designated RFID tags in the study area in autopilot approach mode to receive the RFID signal (Figure 7); the moving speed was 5 m/s (18 km/h) at a height of 30 m from the sea surface (Figure 7). The 200 RFID tags fixed on the oyster farming rafts were discretely distributed along the coast of Chiayi County. The positions of the rafts with RFID tags were also recorded by a handheld GPS (Model: Garmin eTrex 32x) and used as reference points to calculate the distance from the estimated tag points. Figure 7 shows the spatial distribution of the 200 RFID tags identified by the autopilot experiment. The spatial bias between the positions of the RFID-drone tags and the handheld GPS ranged from 2.38 to 59.99 m with a mean localization difference of 30.92 m (Figure 8).

3.2. Spatial bias of the RFID-GPS hybrid system

The RFID-GPS hybrid system experiment was conducted on December 2020; 20 tags were fixed to the oyster farming rafts and placed in the designated culture area. The positions of the RFID tags were recorded using a handheld GPS device. The results show that RFID signal transmission over seawater is completely feasible in line-of-sight (LOS) conditions, and 20 tags were comprehensively identified. Figure 9 shows a diagram of the spatial distribution of the 20 RFID-GPS hybrid tags. According to the result, the spatial bias between the positions of the RFID-drone system and the handheld GPS ranged from 1.27 to 10.47 m; the probability of a localization difference of less than 5 m was 45%, with a mean error of 5.34 m (Figure 10).
Figure 11 shows the displacement biases between the reference points (first signal received by the onshore station), and the subsequent position of each tag varied within 72 h. The average hourly displacement bias of 20 RFID tags ranged from 3.64 m to 18.32 m with an average of 11.68 m, while a maximum displacement bias of 35 m was found approximately every 12 hours. Particularly, regular spatial displacement fluctuations suggested that the astronomical tide was the primary cause for the spatial bias of oyster farming rafts. Moreover, regular bias fluctuation of each raft per hour may be related to the varied anchor line length rather than the spacing between the rafts themselves.

3.3. Feasibility of oyster raft monitoring

The experimental results of the two RFID systems show that the mean position accuracy of the RFID-GPS hybrid system is higher than that of the RFID-
Figure 9. Spatial distribution of 20 RFID-GPS hybrid tags; the black circles indicate the positions of the RFID-GPS hybrid tags recorded by a handheld GPS; the yellow circles indicate the positions of the RFID-GPS hybrid tags received by the onshore station.

Figure 10. Spatial bias of the RFID-GPS hybrid system.

Figure 11. Displacement bias of the RFID tags in 72 hours. Grey dots indicate displacement bias of individual rafts, and the red line is the average bias of all rafts monitored per hour.
drone system. Thus, the RFID-GPS hybrid system was employed to acquire the positions and identifications of oyster farming rafts from the satellite images.

In January 2021, 50 RFID-GPS hybrid tags were scattered from the rafts by oyster farmers, and their signals were identified (yellow circles in Figure 12). SPOT-7 satellite images taken at 10:24:53 (UTC+8) on 16 January 2021, over the oyster farming area were processed to detect the rafts (black circles in Figure 12). Figure 12 shows the composite features of raft positions from satellite and RFID-GPS hybrid tags within a 1 h interval (referring to the acquisition time of the satellite image). The positions of the RFID-GPS hybrid tags (circles in yellow) were correspondingly superimposed with those of the rafts in the satellite image, whereas the raft positions determined by image processing were identical to those of the rafts in the satellite image. Accordingly, raft positions identified from satellite images were used as the reference points for validation with RFID-GPS hybrid tags, whereas localization results (Figure 13) showed a mean spatial difference of 12.08 m. Most of the tags (58%) had a difference smaller than 12 m. Furthermore, the receiving distance for the tags from the ground station was 2.42–3.63 km, where all tags in the area were identified with RSSI values ranging from −82 to −96 dBm (Figure 13). The signal of the tags dissipated with distance from the ground station and did not reveal a certain relationship, thus indicating that the signal strength on the water surface may greatly affect the accuracy of the retrieved position without embedded GPS signals.

4. Discussion
4.1. Accuracy and localization

The results of the RFID-drone system autopilot experiment showed that the RFID-drone system worked efficiently in the marine environment. However, two major factors could cause localization differences. First, the flying height of the drone was 30 m above the sea surface, which may cause the reception of crowded signals by the onboard RFID reader, which

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**Figure 12.** (a) Spatial distribution of 50 RFID-GPS hybrid tags. The point feature of oyster farming rafts was generated based on a SPOT–7 satellite image from 16 January 2021. (b) Composite features of the raft positions from satellite and RFID-GPS hybrid tags.
interferes with the calculation of the median position of the RFID tags. Moreover, the RSSI from the tags did not vary with horizontal distance. Second, oyster farming rafts are possibly moved by tidal currents, as their anchor strengths are less than the stress. Cruz and Pedrasa (2019) indicated that the localization algorithm applied to RSSI may improve the accuracy of the active RFID system; however, our results for RSSI varied with distance from the sea (Figure 13). This may increase the uncertainty in the position-retrieval process. Moreover, the detection frequency for rafts was unsatisfactory because of limited drone endurance, appropriate weather conditions, and the manual localization process.

The RFID-GPS hybrid system completely identified all tags from ground receiving stations and directly obtained the positions by deciphering the latitude and longitude signals of the GPS embedded in the tags. The potential of the RFID system over seawater reaches 3.57 km; thus, the proposed RFID system feasibly covers the oyster farming area with a land-based receiver. Furthermore, the transmissions are feasible using low-cost RFID UHF antennas, making them useful in commercial deployments. The results of the present study demonstrate that the proposed RFID-GPS hybrid system performs well in monitoring oyster farming rafts. Combining satellite image raft detection further improved the oyster farming surveillance process. For example, oyster rafts are widely distributed in the sea, whereas unregistered rafts can be distinguished by integrating the positions derived from RFID-GPS identification and satellite image detection. Moreover, the advantages and limitations of our RFID-GPS hybrid system were compared with previous similar studies (Table 6), which showed that our design could provide the advantage.

Figure 13. (a) Distance between the position of RFID-GPS hybrid tags and the position of oyster farming rafts detected from the satellite image. (b) RSSI distribution versus reading distance.
Table 6. Comparison of RFID systems applications.

| Application                        | Wireless technology | Advantages                        | Limitations                  | Reference                        |
|------------------------------------|---------------------|-----------------------------------|------------------------------|----------------------------------|
| Fish tracking                      | RFID and GPS        | Real-time tracking; Cost-efficient| Short range                 | (Bennett et al. 2016)            |
| Fish catch information management system | RFID, GPS and communications satellite | Real-time tracking; Low cost | Short range                 | (Miyamoto et al. 2006)           |
| Fishing gear identification        | RFID                | Low cost; Real-time tracking       | Short range; Low readability | (La Velley, Brickett, and Moffat 2010) |
| Fishing gear position marking      | RFID                | Long range; Real-time tracking     | LOS transmission; Sensitive to environment | (BIM 2007)                       |
| Automatic system for monitoring fishing effort | RFID and GPS | Low cost; Real-time tracking       | Short range                 | (Uchida et al. 2005)             |
| Aquaculture devices monitoring     | RFID and GPS        | Long range; Real-time tracking; small spatial bias | LOS transmission | Our research                     |

of long-distance monitoring with real-time frequency (1 signal per hour) and small spatial bias (<11 m). The limitation of our design system is the LOS transmission, which cannot widely receive tag signals from a single antenna. Consequently, this approach can be used in other sectors of marine industry monitoring worldwide, such as aquaculture cage positioning and recreational device identification.

4.2. Challenges and suggestions

RFID tags are not guaranteed to be failure-free, and approximately 20%–30% of RFID tags have manufacturing defects (Kaur et al. 2011). Furthermore, use-related battery drainage or water damage to RFID tags is difficult to detect. We have proposed several suggestions for future research. First, observations should be used to determine whether temperature and various weather conditions affect the functionality and efficiency of an RFID system. Second, GPS accuracy should be improved with a specially designed antenna (Khosravi, Moghadas, and Mousavi 2015). Due to the complex marine environment and high reflectance of the sea surface, the GNSS antenna receives more signals from the water surface reflection (Cui and Kouguuchi 2011; He and Suuronen 2018; Rumora, Sikirica, and Filjar 2018), which deteriorates the accuracy of GPS position estimation. Third, the power supply should be improved for more sustainable use in marine environments. The power of the 3 V batteries used in the current experiment is insufficient to provide continuous data transmission for longer than one year, while tags release hourly signals. Limitations include the difficulty of replacement and the risk of losing power during the operation. Therefore, alternative power supply options for RFID tags must be explored in the future (Xu et al. 2019). Fourth, compatibility and connections should be enhanced using wireless sensors. The integration of RFID and WSN technologies will expand multiple applications owing to the necessity of detecting environmental conditions and obtaining aquaculture-related information (Duroc and Kaddour 2012; Ortega-Corral et al. 2017).

5. Conclusions

In this study, two monitoring systems that integrate RFID systems and GPS sensors were proposed and implemented to monitor oyster farming rafts. The experiments indicated that both systems worked properly in marine environments, while the proposed RFID-GPS hybrid system was more efficient and accurate for object monitoring. The results of the RFID-GPS hybrid system showed signal reception distances greater than 3.6 km from the coast (where most oyster rafts are distributed) with a spatial bias lower than 11 m (average length and width of oyster rafts are 8 m and 12 m, respectively). Moreover, the designed tags can also release signals which are received hourly for eight months. Accordingly, RFID-GPS hybrid tags and systems are sufficient for monitoring devices with high spatial accuracy and frequency in coastal waters. Furthermore, the positions of the RFID-GPS hybrid tags were compared with satellite images to efficiently identify the spatial distribution of oyster farming rafts, thus, saving manpower and time. Importantly, the power supply of RFID tags played an important role in RFID systems. The principal limitation of the RFID-drone system is the flight time of the drone. The hovering time of the drone is a critical factor in autopilot experiments. In summary, the experiment confirmed the feasibility of the RFID-GPS hybrid system for monitoring oyster
farming rafts. The proposed RFID-GPS system provides an efficient approach for acquiring dynamic information on oyster rafts and helps improve the marine debris problem with real-time information on oyster farming raft positions. Additionally, the study strongly recommends regular monitoring of multiple industrial and recreational marine devices.

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**Data and codes availability statement**

The data that support the findings of this study are available from the corresponding author, [Y, Chang], upon reasonable request.

**Disclosure statement**

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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