Developing Sense and Avoid (SAA) Capability in Small Unmanned Aircraft

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Abstract

This projects aim was to design, build and test a sense and avoid (SAA) system suitable for use on a small unmanned aerial vehicle (sUAV). Current CAA regulations and existing systems were reviewed before the decision was made to use ultrasonic sensors for the main sensing element. The SAA system consists of four SRF01 rangefinders, connected on a serial bus to an Arduino which filters the signals between the receiver and flight control board, allowing it to be fitted to a wide range of VTOL UAVs. The SAA has a mass of 0.024 kg and a component cost of £91. In order to test the system, an X8 co-axial multi-rotor was designed and built that has a MTOM of 0.278 kg. During testing it was found that acoustic noise from the propellers reduced the sensors usable range to approx. 0.75 m, thus limiting the maximum forward velocity. However, the system was still proven to work as expected during flight trials.

Introduction

With the increasing use of small UAVs in both civilian and military aviation, air regulators are calling for sense and avoid (SAA) systems to be developed [1]. When operational, these systems would allow UAVs to integrate into controlled airspace. SAA could also be used to operate indoors by detecting obstacles in the flight path.

This research focuses on VTOL UAVs with an MTOM of less than 2 kg, such as multi-rotors. This mass limit was chosen as it is the definition being adopted by regulators including the FAA [2]. This limit means the SAA system must be very light in order not to affect the UAVs performance.

This project aims to answer the following research questions:

1. Which type of sensor provides the best performance for SAA on a small VTOL UAV?
2. Can a SAA system be designed that is configurable for use on as many different VTOL UAVs as possible?
3. Can a SAA system weigh less than 0.050 kg

Current Systems

SAA systems have been designed that are suitable for small UAVs. These typically use either infrared or ultrasonic rangefinders for their low mass, small size and low power consumption. One such system, designed at the University of Wurzburg [3] uses twelve SRF02 ultrasonic sensors (Figure 1) to provide a 360° field of view, giving a mass of 0.055 kg for the sensors alone. It has a maximum range of 2.5 m and slows the multi-rotor down based on its proximity to an obstacle before holding position a pre-set distance away. It cannot be used on other multi-rotors without major modification as it is integral to the flight controller.

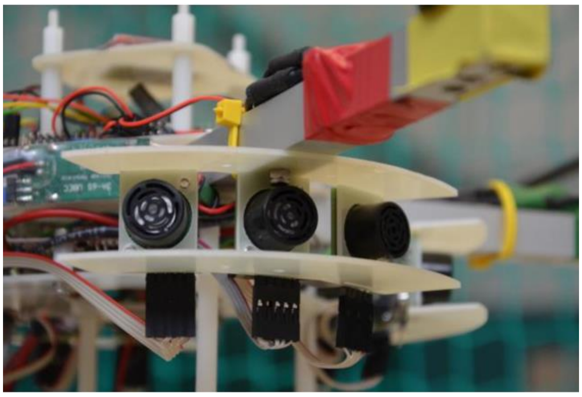

Figure 1: An ultrasonic SAA system [3].

Infrared systems function in a similar manner (Figure 2). A system developed by Julio uses four sensors which is found to save weight and provide an adequate field of view. Infrared sensors return range data faster; allowing for quicker reaction times however, they can only range up to 1.5 m and therefore the UAVs speed is still restricted in order to give the system time to react to an obstacle [4].

The sensor technology chosen for this project is ultrasonic. This is because they are typically lower mass and more compact than infrared sensors, whilst offering up to four times the range. Also, infrared sensors are more affected by their operating environment. They cannot function in low visibility conditions such as smoke and suffer interference from the sun. This would limit the systems performance and the conditions in which it could operate.

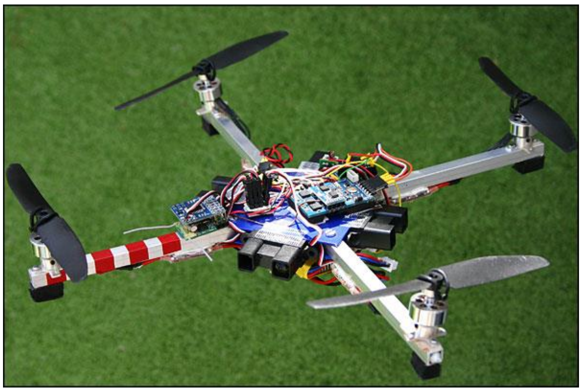

Figure 2: An Infrared SAA system [4].

As ultrasonic sensors find ranges by timing how long it takes to receive an echo, they are sensitive to the echo's amplitude. This causes some disadvantages which affects their performance on VTOL UAVs. If the material being detected isn't acoustically reflective, such as sponge, then the echo will have low energy when it returns to the transducer. This could lead to some materials not being detected at long ranges. Ultrasonic rangers are also sensitive to noise sources present on UAVs. This will form part of the investigation.

Methodology

The project used an experimental methodology. A SAA system and the multi-rotor were designed, built and tested to evaluate the use of ultrasonic sensors in a lightweight SAA system.

Multi-rotor

To test the system, a multi-rotor was needed. As there wasn't a suitable platform available, an X8 multi-rotor was purpose built (Figure 3). To allow for indoor flight, it is based on a 0.24 m carbon fibre frame. It uses eight brushless outrunner motors arranged coaxially fitted with 5030 props. This makes it an X8 and provides redundancy in the event of a single motor/rotor failure. Stability is handled by a KK2 flight control board. This was chosen for its self-level mode and LCD screen making setup and flying easy. Power comes from a 2 cell 1600 mAh Li-Po battery which gives flight times of around 8 minutes. The multi-rotor is controlled from a 5 channel transmitter where the fifth channel is used to toggle the SAA system on and off during flight. In total, the multi-rotor has a MTOM of 0.278 kg, meaning the mass of the SAA system was severely constrained.

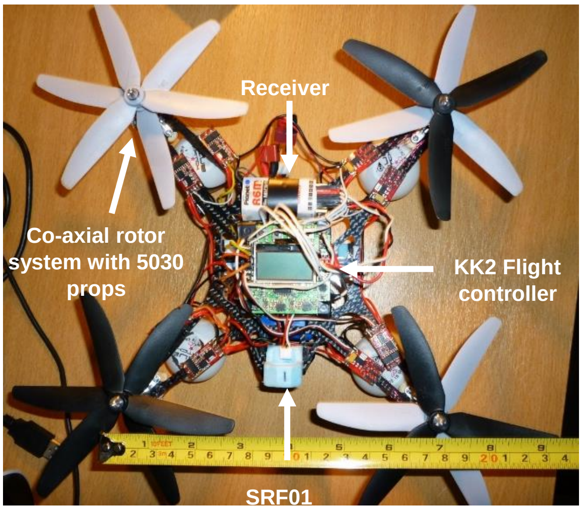

Figure 3: X8 multi-rotor with SAA system.

Sensor Choice

Several different ultrasonic rangefinders were compared before the decision was made to use the SRF01 sensor from Devantech (Figure 4). The sensors specification is given in Table 1 and Figure 5 shows a polar plot of the sensors detection zone. It was chosen as it was the lowest mass sensor available at just 0.003 kg. Also its single wire serial communication allows up to sixteen sensors to be run from one microcontroller port.

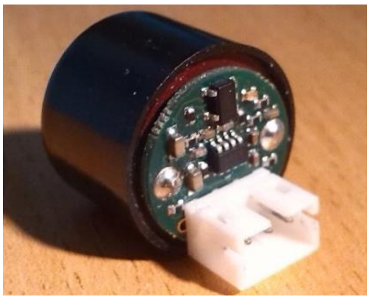

Figure 4: SRF01 sensor.

The sensors sensitivity to objects was tested with a variety of materials. As expected, the SRF01 was unable to detect soft materials such as foam at any range, but could detect materials to within the sensors 0.03 m accuracy.

A multi-rotor presents a very noisy environment for an ultrasonic sensor to operate in. The major sources of noise are frame vibrations, electrical interference and the acoustic and aerodynamic noise from the propellers downwash. Steps were taken during design to mitigate these sources such as mounting the sensors in foam as far from the propellers as possible. The effects of noise on the SRF01 were tested.

Table 1: SRF01 Specification [5].

Specification	SRF01
Frequency (kHz)	40
Mass (kg)	0.003
Range (m)	0 – 6
Resolution (m)	± 0.03
Beam angle (°)	55
Cost incl. VAT (£)	20.39
Consumption (mA)	25
Communication	Single wire serial bus

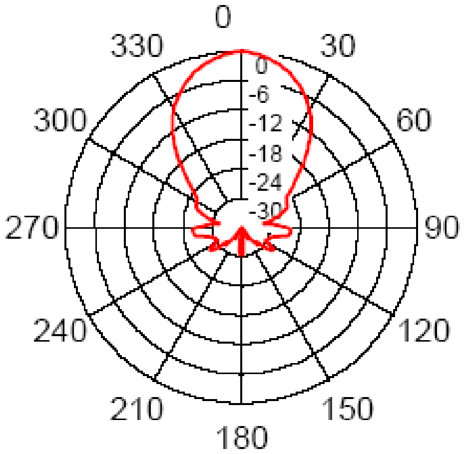

Figure 5: SRF01 beam pattern (vertical axis in decibels) [6].

SAA System

The SAA system consists of four SRF01 sensors connected to an Arduino Nano via a single wire serial bus. The Arduino was used as it was lightweight (0.004 kg), simple to program and had the required digital I/O pins. The Arduino Nano is mounted under the flight controller and can be seen in Figure 7.

The system works by intercepting the throttle, roll and pitch channels between the receiver and flight controller. It reads the servo pulses using interrupts and compares them to the ranges from the relevant sensor. It then decides whether to allow the command to be sent to the flight controller. For example, if the user tries to steer forwards whilst the sensors detect an obstacle within the threshold distance (e.g. 0.50 m). The controller will block the command and instead give the command for the multi-rotor to stop and hover in position. An example of the Arduino code used to filter pitch commands is shown below. The multiple IF statements ensure processing is only carried out if the control input changes.

```
  forwards = SonarFwd(); // find forwards range

// filter pitch command and block if obstacle detected
  if(bUpdateFlags & ELE_FLAG)
  {
   if(servoELE.readMicroseconds() != unELEIn)
   {
    // check if steering forwards and if there is an obstacle
    if(unELEIn < ELE_Zero & forwards < threshold)
    {
     // if collision is possible then output zero command
     servoELE.writeMicroseconds (ELE_Zero);
    }
    else
    {
     // Divide commands by 2 to limit the multi-rotors speed
     SpeedELE = ELE_Zero + ((unELEIn - ELE_Zero)/2);
     servoELE.writeMicroseconds (speedELE);
    }
   }
  }
```

SonarFwd is the function used to communicate with the forward facing sensor. It returns the range in cm. The sensors were originally controlled using software serial, however this was found to cause a timer conflict with the servo pulses. This meant the hardware serial ports had to be used at the expense of having the USB port available for data collection.

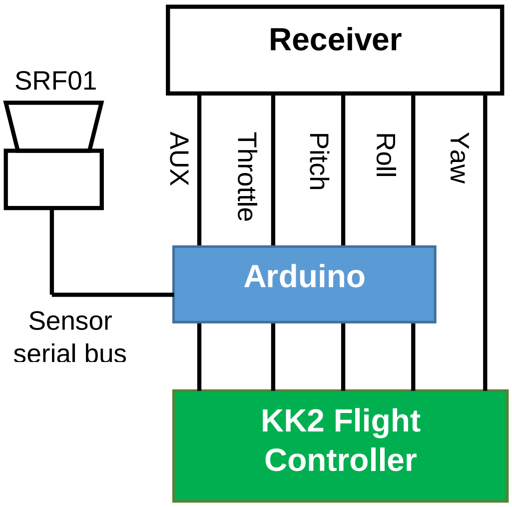

Figure 6: SAA system circuit diagram.

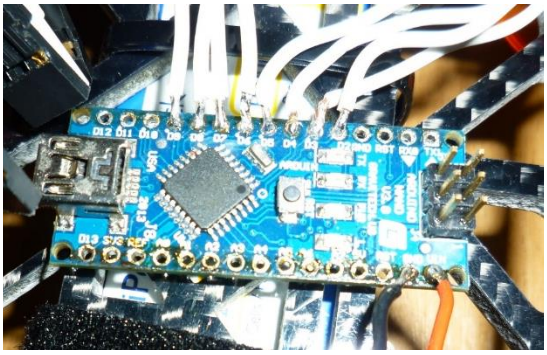

Figure 7: Arduino mounted beneath KK2.

Putting the SAA system between the receiver and flight controller means that it can be easily installed on any multi-rotor. The sensors serial bus allows up to sixteen sensors to operate on the same wire which makes the system very versatile.

The complete system weighs 0.024 kg and had a component cost of £91. It provides a 165° field of view forwards, left, right and down (Figure 8).

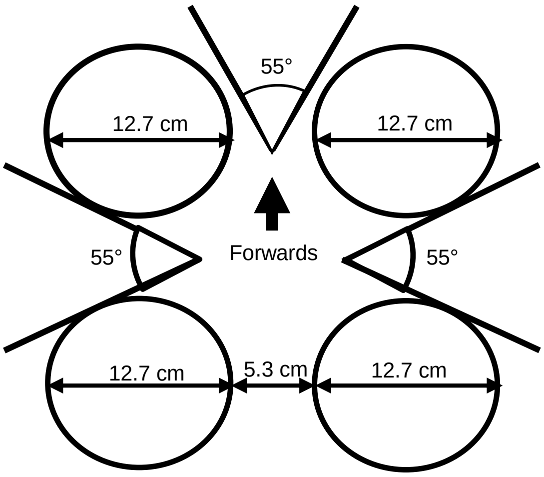

Figure 8: SAA system field of view.

Noise Testing

The effect of noise on the sensors was tested by placing a cardboard obstacle in front of the multi-rotor on the ground. The multi-rotor was held down whilst the motors were run at full throttle to simulate the noisiest possible conditions. 100 readings were taken from the sensor and plotted. The test was carried out at 1.5 m, 1 m and 0.5 m intervals.

Figure 9 shows the results for 1.5 m. It was found that the sensors were unable to detect the obstacle. Instead the obstacle was masked by noisy false detections. These are likely to be caused by acoustic noise from the propellers adding energy at the transducer which is read as a return echo.

Figure 10 shows the results for 1 m. The sensors were able to see the obstacle but the readings are still dominated by noise. The lowest reading is 0.81 m, so the threshold distance for the system must be below this value.

Figure 11 shows the results for 0.5 m. At this range, the sensors can detect the obstacle accurately. There is still minimal noise present, possibly caused by electrical interference.

The excessive noise means that the systems threshold distance was set at 0.75 m in order to be below the false detections. This doesn't give the system much space to detect the obstacle and stop the multi-rotor. Therefore the multi-rotors speed had to be limited with the system active, this was achieved within the code by dividing the inputs by two, halving the speed. This means the limit is lifted when the SAA system is switched off.

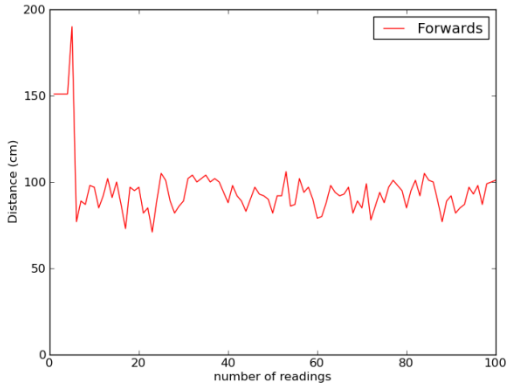

Figure 9: Results for 1.5 m.

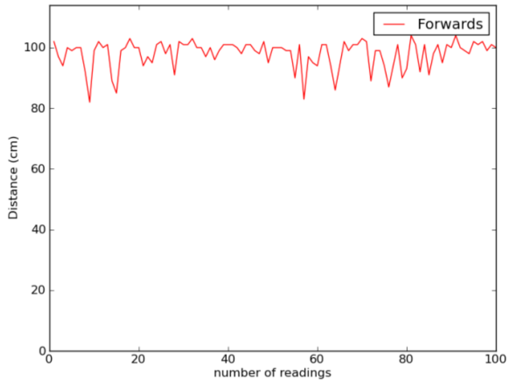

Figure 10: Results for 1 m.

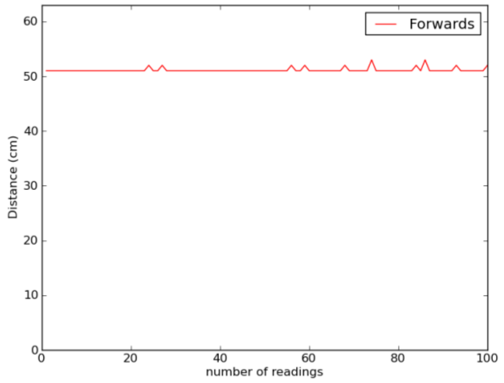

Figure 11: Results for 0.5 m.

Flight Testing

The SAA system was tested indoors and outdoors by flying the multi-rotor towards a cardboard obstacle that could be moved to prevent a crash. Due to the USB port being taken up with the sensors, there was no way to obtain data from the system during operation. Therefore visual observations were made on the systems behaviour.

The multi-rotor approached the obstacle until it was within 0.75 m when it levelled out into hovering flight and held position approximately 0.5 m away. This distance varied if there was a gust or the throttle setting changed. While the multi-rotor was within 0.75 m of the obstacle, forward pitch inputs were ignored. All other controls worked normally and if the stick was pulled back then the multi-rotor flew away from the obstacle. This test was repeated for the left and right sensors. In both cases the system responded in the same way with any roll inputs in the direction of the obstacle being ignored.

One problem highlighted by flight testing was that the multi-rotor could drift into the obstacle if there was a breeze or it was out of trim. This is due to the system simply blocking controls by sending the signal which makes the multi-rotor stop and hover. To prevent drifting into an obstacle, the SAA system must actively maintain a safe distance. This is an improvement that should be made for future systems.

Conclusion

Overall, this project has answered the three research questions posed at the beginning. The final system mass of 0.024 kg is well below the 0.050 kg target and shows that SAA systems can be made for UAVs where mass is severely constrained.

The decision to use ultrasonic sensors for SAA on VTOL UAVs was found to be a suitable choice. The SRF01 sensors provided sufficient range and accuracy against all but the most acoustically absorbent materials. However, their sensitivity to the propellers acoustic noise turned out be a major drawback. Limiting their usable range to 0.75 m, this in turn limited the multi-rotors speed whilst using the system. This is a big limitation but could be removed through the use of shrouding.

This systems advantage over others is that it is easily configurable. Designing the system to act as a filter between the receiver and flight controller allows it to be fitted to most VTOL UAVs without major modifications to the UAV. Also, the serial bus communication allows sensors to be easily added and removed as required for different applications.

Future work to improve the systems performance should include:

- Shrouding the sensors to reduce the acoustic energy from the propellers that can reach the transducer. This should improve the range and therefore the speed the system can be used at.
- Use PID control to prevent drifting by maintaining a constant safe distance from an obstacle. This will allow the system to also work well outside.
- Add an altitude hold function using the downwards facing sensor.
- Find a way to obtain data from the system during flight to better assess performance. Possibly using wireless communication or visual tracking.

References

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