Object Tracking Using Drone Swarms

E25

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EXECUTIVE SUMMARY

The Wireless Research Centre has sponsored a project which aims to use drones to track small objects such as insects. The envisioned system will consist of five drones forming a swarm. The swarm will follow a target that is equipped with a harmonic radar transceiver. The main motivator for this project is the need to track insects to monitor their behaviour. Conservation groups can use this technology to track endangered insects. The ability to monitor their behaviour will assist in conservation efforts. Farmers, importers, and exporters can use drone swarms to track invasive insects and pests. The ability to track how invasive insects move will prevent them from establishing within New Zealand's borders.

The swarm will consist of one transmitter drone and four receiver drones. A harmonic transceiver will be mounted on the target. The harmonic transceiver can receive a radar signal and re-emit it at a harmonic of the original frequency. The receiver drones can detect this harmonic signal and will use multilateration to determine the target's location. The technology required to mount a harmonic radar system on a drone is still in development. In the absence of this technology, harmonic radar data will be simulated based on the GPS position of the target. The target will broadcast its GPS location and the transmitter drone will convert this to harmonic radar ranges.

The drone swarm must meet the following requirements to be successful. The swarm must follow a moving target – either a person walking with a laptop or another drone. The swarm must implement safety measures to reduce the risks associated with collision, power loss, signal loss, and several other potential safety hazards. The swarm must use four existing drones owned by the WRC. The swarm must easily integrate with the harmonic radar hardware when the technology it is ready.

This project is a continuation of a final year project from 2020 which culminated in a successful flight of one drone tracking a target. At this stage, the data from last year's flights has been analysed and several areas for improvement were found. It was decided that a Kalman Filter should be implemented to reduce the noise in the GPS redouts. The filter would also employ an improved multilateration algorithm to track the target more accurately. My main task was to build and test this filter. The filter robustness was tested in response to extreme noise and sensor dropout. The filter could continue to operate with both these factors.

The next milestone in this project is a repeat of a demonstration that was attempted last year. In this demonstration two real drones and three simulated drones tracked a target. This test will have improved data logging to identify any new issues in the code. The team will use the data from this test to improve the design and allow the system to fly all four drones without any being simulated. In parallel to this, the multilateration algorithm and Kalman Filter will be incorporated into the code from last year's team. Once all four drones in the swarm are successfully flying, the filter and multilateration algorithms will be added. The project will culminate in a demonstration where the swarm will accurately track a target using emulated radar data.

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I. PROJECT OVERVIEW

A. *Background*

This project, sponsored by the Wireless Research Centre (WRC), aims to use drone swarms to autonomously track an object in 3D space. The main motivator for this project is the need to track insects to monitor their behaviour. New Zealand maintains a unique and diverse ecosystem that cannot be found anywhere else in the world. Insects are a crucial component of this ecosystem as they maintain many ecological processes. Therefore conserving native insects and preventing invasive insects from entering the country. Drone tracking of invasive insects is useful in monitoring their behaviour and locating their nests so they can be eradicated [1]. Drone swarms can also be used to track endangered insects to assist in their preservation.

Parties that could benefit from this project include importers, exporters, farmers, and conservation groups. New Zealand has strict biosecurity laws which importers must adhere to. Drone tracking may be employed by importers as another security layer to eradicate invasive insects that get past all other countermeasures. New Zealand's exports must be free of insects that may threaten other countries ecosystems. Exporters could use drone swarms to track insects which may survive on their product. Farmers can use drone tracking to monitor and prevent the spread of invasive insects such as weevils which threaten New Zealand farming industry [2]. Conservation groups can use drone tracking to monitor native or productive insects such as bees. The behavioural patterns of many native insects are unknown because they are impossible to track. The ability to track behavioural changes in response to pesticide exposure is useful in the conservation of species such as honeybees [3].

Drone tracking using harmonic radar can theoretically be used to track any object that can carry a transceiver. Harmonic radar transceivers are becoming increasingly small, and light compared to traditional tracking methods such as GPS, and VHF radio modules. Therefore, this technology may be applied to other contexts and will be useful to parties outside the insect tracking field.

B. *System Overview*

The aim of this project is to produce a drone swarm that can follow a ground-based target. This project is a continuation of work done last year which culminated in a demonstration of one real drone and four simulated drones following a target. The drone-based radar transmitter and the harmonic radar transponder are currently being developed independent of this project. In the absence of this technology, radar data will be simulated based on the GPS position of the target. The target will broadcast its GPS location and the transmitter drone will use this data to simulate the harmonic radar. Therefore as a final demonstration of the project, the swarm will follow a ground-based laptop, broadcasting its location. As a stretch goal the swarm may follow a smaller drone, also broadcasting its location.

The system will consist of four receiver drones and one transmitter drone, shown in Figure 1. A harmonic radar system will be deployed on the swarm to track the target. The transmitter drone outputs a radar signal. This signal is taken in by a harmonic transponder mounted on the target and re-emitted at a higher harmonic of the original frequency. The receiver drones detect this harmonic frequency and can use it to determine the location of the target. Because the harmonic transponder emits a higher frequency than it receives, the drones can distinguish the signal emitted by the target from background reflections. The drones' locations will be tracked using GPS. Multilateration will be used to track the target. Multilateration is a strategy that can estimate the position of the target based off the drones' current locations, and the harmonic radar time of arrival (TOA) data. Once the location of the target is estimated the swarm will move to follow the target.

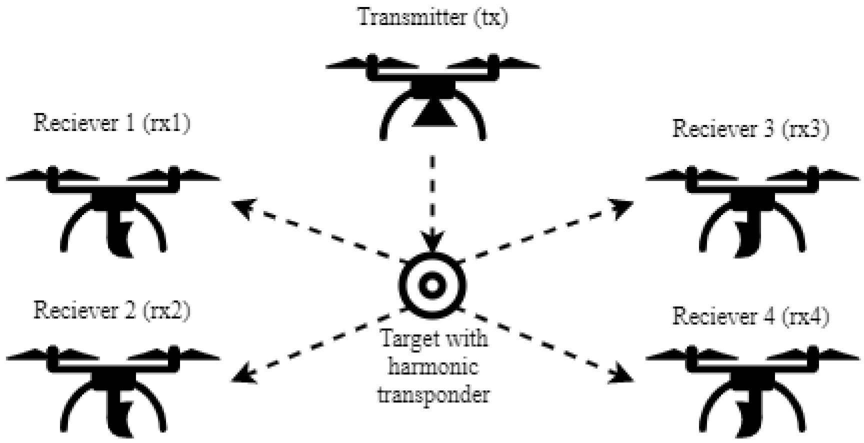

Fig. 1. The drone swarm layout with one RADAR transmitter and four receivers.

C. User Requirements

The solution must meet the following requirements to produce a functional demonstration for the WRC. The swarm must follow a moving target – either a person walking with a laptop or another drone. The swarm will be tuned in a way that allows the target to move as fast as possible while still accurately following the target. The swarm must implement safety measures to reduce the risks associated with collision, power loss, signal loss, and several other potential safety hazards. The swarm must use the existing four rotor drones owned by the WRC. Therefore, the solution must use the Pixhawk flight controller, Intel NUC, sensors, and GPS module on the drones. The swarm must easily integrate with the harmonic radar hardware when it is ready.

D. Project Components

The project was split into several components to allow each team member to work on a part. These components include are Kalman Filtering, multilateration, communication, safety measures, and datalogging. This report details the implementation and testing of the Kalman Filter and its integration with the multilateration algorithm. Each member has mostly worked on their own tasks however work was also shared depending on workloads and skillsets.

II. PROGRESS TO DATE

A. Overview

This project is a continuation of a final year project from 2020. The first step in the development of this project was understanding the progress and pitfalls of last year's team. It was also important to understand their code to integrate new work. The work of last year's team culminated in a demonstration of one drone flying and tracking a target with four simulated drones. The swarm could track person with a laptop moving at walking pace. An additional demonstration was attempted with two drones flying however this was unsuccessful. The swarm generated a critical error which caused the drones to switch to manual control.

Analysis of the Pixhawk log data by Alex Scott logs suggested that anomalous GPS readings triggered an unsafe formation state in the drones even though in reality they were safely positioned. It was determined that filtering the drones' position would prevent this error from occurring as the incorrect reading would be filtered out.

The multilateration algorithm used in last year's project was also identified as a source of error. This algorithm used a 2D grid-based system to estimate the position of the target based on the radar range readings from the drones. The algorithm iterated through integer grid coordinates within the area covered by the drones. At each iteration, the algorithm calculated the radar ranges that would occur if the target were at this location. The calculated ranges were compared to the real ranges. The values that were closest to the real ranges were selected as estimated the position of the target.

The previous years' multilateration algorithm had two major sources of error. Firstly, it only ran in two dimensions whereas the real radar readings are in three dimensions. Therefore, changes in the target's altitude will affect the result. Secondly the use of a grid-based system restricted the accuracy of the result to the nearest integer. An increase in accuracy was possible using this algorithm by decreasing the grid size. However this would require a significant increase in computational power. Therefore a new 3D multilateration algorithm would be designed and incorporated into the filter. This algorithm was required to be computationally efficient, work in 3D space, and produce accurate readings when noise and sensor dropout are introduced.

B. Path and Radar Emulation

A program that could generate a target path independent of the drones was developed by Oli Dale. This program took a timestep, a maximum displacement, velocity, and acceleration as inputs and produced a list of 3D coordinates which represented the path of a simulated target. This program was used extensively during the development of the filter to test its performance. The filter output could be compared to the simulated path to quantitatively measure error – something that was not possible while flying the real drones. Furthermore the movement characteristics of the target, such as its maximum velocity could be altered to test how the filter responds to different types of target. For instance one could increase the maximum velocity to simulate a bird or increase maximum acceleration to simulate a small insect.

The harmonic radar which was to be deployed on the drones was not fully developed. Therefore, an algorithm that could simulate radar ranges in 3D needed to be built. This algorithm, also developed by Oli Dale, took the GPS position of all five drones and the target path as inputs. It generated a set of four ranges, simulating a range reading from each receiver drone. Additionally, normally distributed noise could be added by specifying an amplitude. Using this feature the capacity of the filter to remove noise could be tested.

C. Multilateration

To design a filter for the drones the radar system must be understood. A radar signal is emitted by the transmitter to measure the distance to the target. This signal reflects off the target and is received by the four receiver drones at different times. Therefore, the output from the harmonic radar consists of five time readings. The time at which the radar signal is sent and the times when the four receiver drones detect the signal. In this project the transmitter and receivers are on different drones. It is important that all drones share a common time base so that the sending and receiving times can be accurately compared. This problem is exceedingly difficult to solve and is outside the scope of this project. Therefore, it will be assumed that all drones share a common time base.

Multilateration is a technique used to determine the position of a target based on the time of arrival of several radar signals. This project was to use multilateration to determine the position of the target. There are two commonly used multilateration algorithms: time sum of arrival (TSOA), and time difference of arrival (TDOA). TSOA requires the time between the signal being sent and being received. The distance to the target may be found by multiplying this time by the speed of light, c. Using this distance, an ellipse can be drawn which represents the possible locations of the target. By repeating this process for multiple drones several spheres can be drawn and the position of the target can be found. This is shown in Figure 2. TDOA uses the differences in the time of arrival of the four radar. The TDOA method also multiplies by c to yield a difference in distance between the target and the drones. By comparing theses distances hyperbola can be drawn between the drones. The intersections of these hyperbola represent the position of the target.

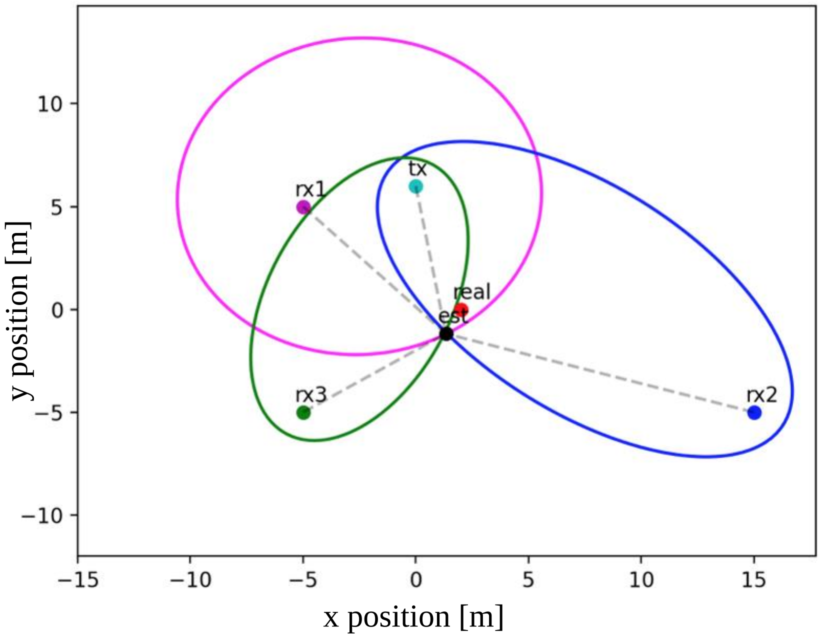

Fig. 2. 2D example of range ellipses for TSOA algorithm.

One of these methods needed to be chosen for the drone swarm project. TDOA does not require the time of transmission to determine a location whereas TSOA does. Therefore, TDOA is suited to applications where one receiver receives a radar signal from many transmitters to triangulate its location. This project uses one transmitter and four receivers. As a result, data transmission is required for both TDOA and TSOA. TSOA performs more accurately when noise is added. This is due to the finite length ellipses used in the TSOA method compared to the infinite length hyperbola used in TDOA. Therefore the decision was made in collaboration with Oli Dale to use TSOA for this project. Equation 1 shows a general version of the TSOA equation used in the filter. For 3D multilateration four equations were used. r_n is the range from drone n. The tx subscript represents a coordinate of the transmitter. The rxn subscript represents a coordinate for receiver drone n. x, y, and z are the coordinates of the target to be found.

$$r_n = \sqrt{(x_{tx} - x)^2 + (y_{tx} - y)^2 + (z_{tx} - z)^2} + \sqrt{(x_{rxn} - x)^2 + (y_{rxn} - y)^2 + (z_{rxn} - z)^2} \quad (1)$$

D. Kalman Filtering

1. Overview

A Kalman Filter was chosen for this project. A Kalman Filter is a type of Bayesian filter that compares sensor measurements with model predictions to produce a more accurate estimate than either option alone. This type of filter was chosen as it could model the five drones in the swarm and the target simultaneously using a constant velocity model. Furthermore, the filter is computationally light and produces an estimate along with a standard deviation as an output. A specific variety of Kalman Filter called the Unscented Kalman Filter was used [4]. This type of filter was chosen as it efficiently deals with the non-linear nature of the TSOA equations. This is done by sampling a few differently weighted points from the nonlinear function then using theses to produce a linear approximation.

Two other alternatives to the Unscented Kalman Filter were also considered. These were the Extended Kalman Filter [5] and the Particle Filter. Extended Kalman Filters perform a similar linear approximation to the unscented variety however they use Taylor Approximation which are more computationally expensive. Particle filters use many non-Gaussian samples (particles) to produce an accurate approximation of the system [6]. However, these filters are computationally intense and difficult to tune.

2. Modelling the Swarm

The target position and the drones' position were both modelled within the Kalman Filter. This was done to minimise the effects of dropout and incorrect GPS readings. A constant velocity model was used within the filter to predict the position, $\boldsymbol{x}_t$, and velocity, $\dot{\boldsymbol{x}}_t$, of all five drones and the target in 3D space. Equations 2 and 3 were used to achieve this. The Kalman Filter compares the model predictions to the sensor outputs and produces an estimate of the locations of the target and the drones. Next, the positions of the drones are updated such that the receiver drones are 10m above the target and 15m from each other. The transmitter drone moves to 10m above the target. The process is repeated at the next position and is shown in Figure 3.

$$\boldsymbol{x}_{t+\Delta t} = \boldsymbol{x}_t + \dot{\boldsymbol{x}}_t \Delta t \quad (2)$$

$$\dot{\boldsymbol{x}}_{t+\Delta t} = \dot{\boldsymbol{x}}_t \quad (3)$$

3. Time Synchronization and Dropout

To simplify the tracking problem for the multilateration algorithm the assumption was made that the drones share a constant time base. In reality this is not true. The range data will not be received simultaneously at each time step and will instead 'trickle' in as it is generated. The Kalman Filter is required to deal with this irregularity. To achieve this the filter updates its state once a second whether it has all the data or not. If a piece of data has not been received only the prediction is used to estimate the next state of the model. This solves the data loss problem and allows the filter to handle short drops in data.

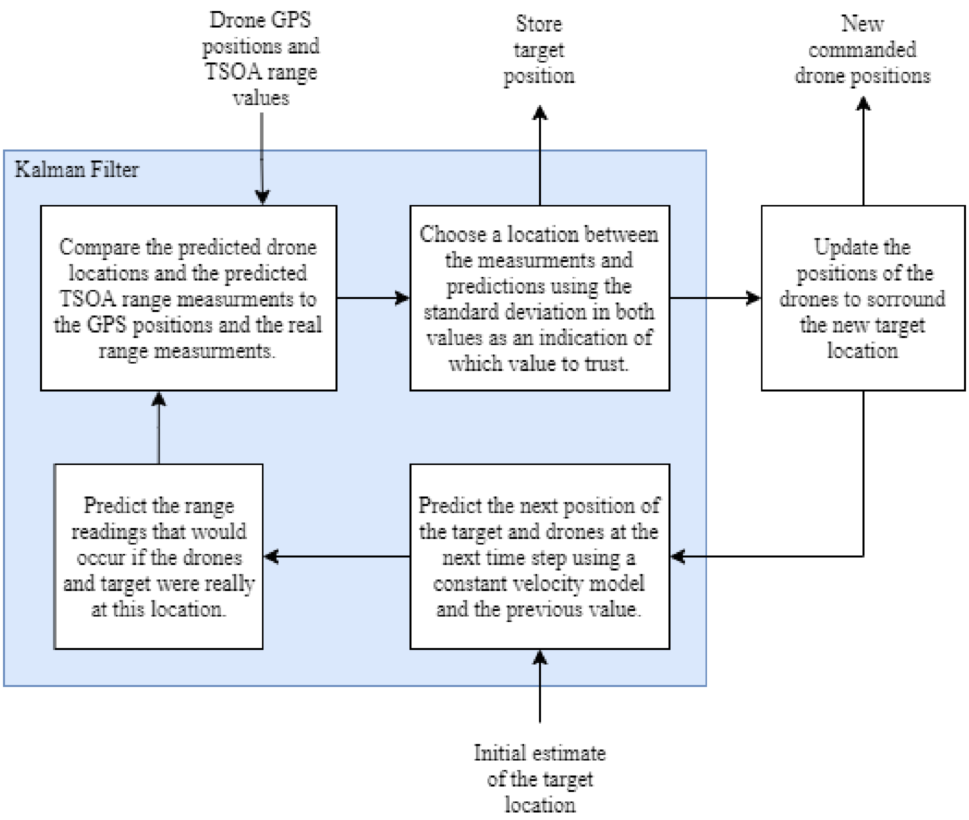

Fig. 3. Flow chart showing the filter and swarm model logic.

4. Visualization and Testing

Once the Kalman Filter was built its robustness to noise and dropout were tested. The exact configuration of the swarm was not yet known so estimates of the levels of sensor noise were used. Figure 5 shows the 3D path of the swarm following a target. A five second dropout in range and GPS data was simulated from 10 to 15 seconds. Normally distributed noise was also added to the sensor inputs with a mean amplitude of 1m. maximum speed of the simulated target was 4m/s. The error in the system is shown in Figure 4.

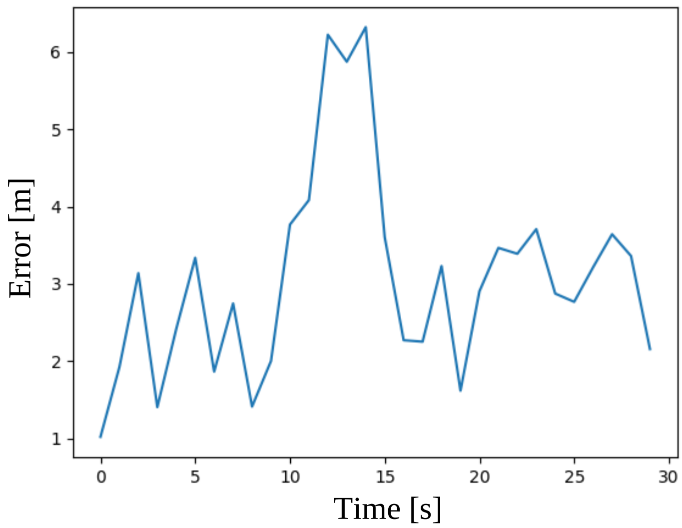

Fig. 4. Absolute error between the real and estimated position of the target.

An increase in error can be seen at 10 seconds due to the drop in readings from rx1 however the swarm continues to follow the target after this. The simulation was run several times with different target paths and the swarm followed the target for all of them. This shows that the filter is robust enough to handle the dropout of one drone for up to 5s.

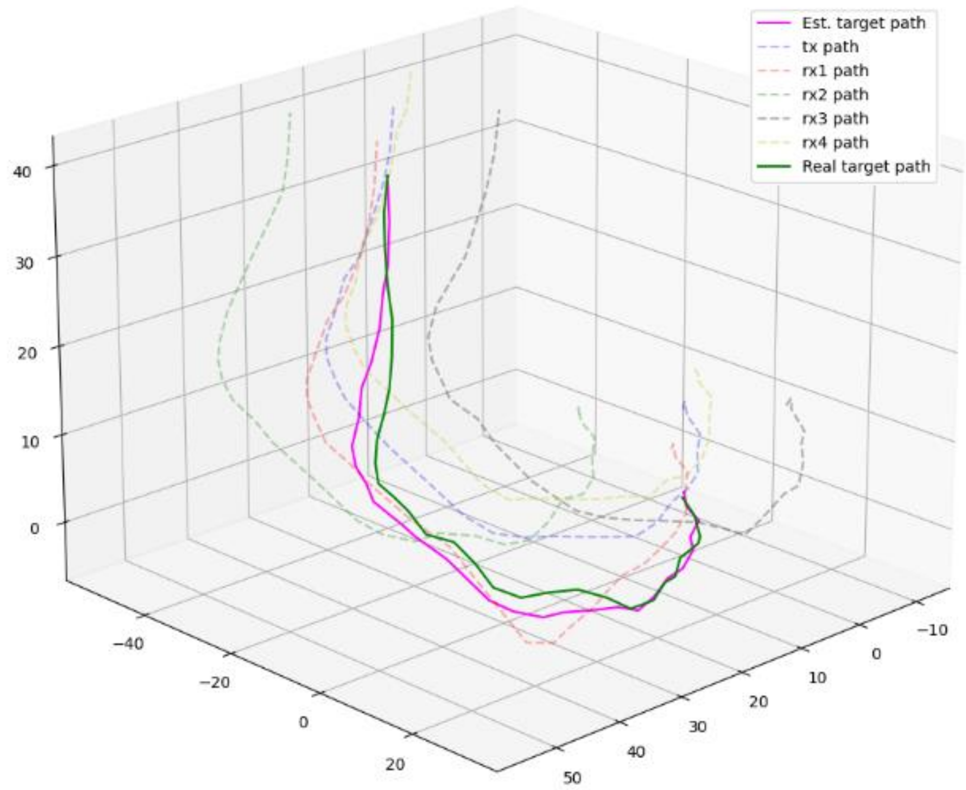

Fig. 5. Comparison between the real and estimated path of the target with a 5s dropout in rx1 at 10s.

Several other non-ideal configurations such as extremely high noise, fast moving targets, and multiple drone dropout were also tested. As a worst-case scenario, normally distributed noise with a mean amplitude of 3m was added to all the sensor measurements. In this case the filter could continue to follow the target however it failed when dropout occurred. The filter was designed such that the noise levels, following distances, initial conditions and variances could be easily tuned as the specifications of the sensors become known.

Three visualisation tools were developed to plot the path, error, and standard deviation in the swarm position. Examples of error and path plots are shown in Figures 4 and 5 respectively. The visualisation tools will be useful when debugging the swarm as they can show in real-time the position of all the drones and the estimated position of the target. In the final demonstration they may be used as an interface with the user.

III. Remaining Tasks

A. *Overall Plan*

The aim of this project is to produce a drone swarm that can follow a ground-based target. An updated project plan was devised to achieve this goal. This is shown in Table 1. Milestone 0 (M0) is a repeat of last year's demonstration where two real drones and three simulated drones track a target. This test will have improved datalogging to identify any issues in the code. Milestone 1A (M1A) is complete when the swarm can follow a target broadcasting its GPS position. Milestone 1B (M1B) is complete when the multilateration algorithm and Kalman Filter can track a target using emulated radar data with added noise. Milestone 2 combines M1A and M1B in a full test where the swarm tracks a target using emulated radar data.

Table 1: Future tasks for the project

Week	Milestone	Team Members				
		Oliver Dale	**Rowan Sinclair**	**Nicholas Ranum**	**Alex Scott**	**Connor O'Reilly**
Mid-year Break	M0 and M1B	Implement multilateration module and test using sim.	Incorporate Kalman Filter and test using sim.	Improve simulation software, launch files, and plotting tools.	Test simulation with two physical drones being held. Full flight test with 2 drones	Improve mothership-slave UAV dependency sync correction software.
1+2		Test robustness of localisation for integration.	Add Loss detection to Kalman Filter and calibrate for practical test.	Investigate the effects of adding artificial network delays / constraints.	Achieve 2 physical drones flying, look to achieve all four drones flying in formation	Account for large higher-order derivatives. Axial rotation around mothership.
3+4	M1A	Perform practical test.	Perform practical test.	Perform practical test.	Perform practical test.	Perform practical test.
5+6		Integrate localisation module into improved communication and swarming code.	Improve tracking capability by measuring noise and reducing dropout.	Investigate methods of reading GPS timestamps to group radar readings.	Optimize landing function. Look to complete milestone 2	Improve swarming states, optimise code efficiency
Mid-sem Break	M2	Prepare for practical test.	Prepare for practical test.	Prepare for practical test	Prepare for practical test	Prepare for practical test
7	Prepare for Final Inspection					
8	**Final Inspection – September 24th**					
9						
10	**Oral Presentation – October 8th**					
11						
12	**Final Report – October 22nd**					

B. Individual Tasks

1. Drone Simulation

The most important incomplete task in this project is getting the full simulation from last year's team working. The simulation runs on Linux and uses Gazebo to simulate the drones. Oli Dale and Nic Ranum have been working on this process however they have encountered constant compatibility issues. As the Kalman Filter is working, my main task will be to work with my team to get the simulation running on our personal computers.

2. Detecting Target Loss

Once the simulation is running, I will attempt to add a feature to the Kalman Filter that can detect if the swarm is no longer tracking the target. This will allow the swarm to operate in a more autonomous manner. The simulation shown in Figures 4 and 5 computes the error in the system by comparing the estimated and exact path of the target. In the final demonstration this is not possible as the exact path of the target will be unknown. The Kalman Filter produces a matrix of residuals which are the differences between the predicted and measured values. The magnitude of values in the residual matrix can be used to decide if the swarm is following the target at a given time step.

3. Incorporating the Filter Into the Swarm

Once the simulation is ready, I can begin to replace the previous multilateration and error detection algorithm with the Kalman Filter. This will require a detailed knowledge of the conventions and logic used in the previous year's code. The Kalman Filter uses cartesian coordinates whereas the drones' produce GPS coordinates in decimal-degrees format. Last year several classes were created to assist in converting between these formats however they will need to be updated to work in 3D. They will also require testing to see how error and noise propagate during the conversion.

IV. SUSTAINABILITY ANALYSIS

A. Environmental Impact

A triple bottom line analysis was used to evaluate the environmental, economic, and social sustainability of a drone swarm. The main motivation for the development of the drone swarm is to track invasive and endangered insects. The movement patterns and behaviour of many small insects is currently unknown as the technology required to track them does not exist. Expensive and environmentally damaging processes are often used as alternatives to tracking.

Tracking the behaviour of endangered insects can help conservationists prevent them from going extinct. For instance, using VHF (very high frequency) radio to track Kākāpō has helped revive the species [7]. However VHF tracking is restricted to larger animals that can carry heavy transmitters. Drone swarms would enable the tracking and conservation of thousands of endangered insects that are too small to be tracked using conventional methods. The ability to easily track invasive insects and eradicate their nests would help maintain New Zealand's unique natural environment. The country's ecosystem is vulnerable to invasive species. For instance human introduced wasps such as the German Wasp, are a significant threat to the country's native bird and insect populations [8].

New Zealand’s export industry must ensure that its produce is free of unwanted pests that may cause havoc if introduced to overseas ecosystems. Methyl bromide fumigation is used to remove pests from timber exports. This gas kills insects such as bark beetles that may have infiltrated the wood after it has been felled. However, the gas is harmful to the ozone layer and is required to be phased out under the Montreal Protocol [9]. Drone tracking can be used to reduce New Zealand’s dependency on the gas by determining when the insects infiltrate the country’s wood exports.

A life cycle analysis of the drones used in this project was performed to assess the environmental impact of the individual components. The major components of the drones including the motors, chassis, battery, controller, sensors and NUC are assembled in New Zealand. The most environmentally damaging of these components to produce is the lithium-ion battery. Mining the lithium and cobalt required to produce these batteries produces significant environmental damage [10]. As the drones are owned by the WRC and are reused each year on new projects this impact is minimised. However if the product was to be widely used, the environmental impact of the batteries must be considered. The drones themselves use little electricity during their flights compared to other insect tracking solutions such as large-scale harmonic radar [11]. Once tracking is complete the harmonic transceiver may be retrieved as it can be tracked indefinitely. This is an improvement over VHF trackers as these have a limited active life and cannot be tracked or retrieved once they run out of power. Therefore they must be left in the environment as litter.

Drone swarms have as smaller environmental impact when compared to other tracking methods such as large-scale harmonic radar and VHF tracking. At a prototype level the environmental impact of producing, using, and recycling the drones is acceptable as they can be reused for other projects. However if the solution was widely adopted the environmental impact of producing and recycling the batteries should be considered. The aforementioned environmental benefits from insect conservation and pest eradication must outweigh the pollution from the drone’s production.

B. Economic Impact

The ability to track and eradicate pests will have a significant positive economic impact on New Zealand’s farming and export industries. Farmers will be able to track the movement of pests across the country and quarantine areas where pest outbreaks occur. This will improve productivity and crop yield [12]. The New Zealand tourism and agriculture industries are dependent on the country’s natural environment. Preserving this environment by protecting endangered species and eradicating invasive ones will benefit these industries and the economy.

This project has inherent research and development costs that must be considered. The drones used in this project were built in New Zealand however they cost approximately $10000 each. This cost is not specific to this project as the drones are a development platform that will also be used for future research projects. If the project is to be economically successful a cheaper drone solution should be developed to reduce initial investment required for the user. The cost benefit from pest eradication and insect conservation must be greater than the initial investment cost of buying the platform.

C. Social Impact

Drone tracking will have a myriad of positive social effects on the project's stakeholders if it is successful. Preventing the spread of invasive insects will protect farmers' and exporters' livelihoods as the chances of a pest outbreak will be reduced. The conservation of native, endangered insects will be easier as tracking will take less effort and time. Finally, New Zealanders will be able to enjoy the country's unique ecosystem free from pests.

The ability to track a target using a small easily hidden transceiver may find uses in other more nefarious fields such as surveillance. It is therefore important that the ethics of individual uses cases for the swarm are properly studied.

Social impacts specific to the use of the drone swarm must also be considered. The drones are dangerous and may harm the user, bystanders, or property if used incorrectly. It is important that the user is well trained and knows the risks associated with using the product. Furthermore safety measures such as safe landing, and target loss detection must be implemented to further reduce the risk of injury. In general the positive social impacts from pest eradication and conservation outweigh the negative impacts from nefarious use cases and risk of injury.

V. CONCLUSIONS

The WRC has sponsored a project with the goal of developing a drone mounted tracking system. A harmonic radar will be deployed on a swarm of five drones to track small objects such as insects. This project is a continuation on work done last year, where a team successfully tracked an object using one real drone and four simulated drones. An attempt was also made last year at flying two real drones and three simulated drones however this was unsuccessful.

This year the project was split into several components including Kalman Filtering, multilateration, communication, safety measures, and datalogging. My task for this project was the Kalman Filter. The Kalman Filter is used for three tasks: Removing anomalous GPS readings from the drones' positions. Tracking and filtering the target's position using the multilateration algorithm and estimating the drone and target positions if dropout occurs.

The Kalman Filter uses a constant velocity model to predict the positions of the drones and target at the next timestep. The filter then compares the model predictions to the sensor outputs and produces an estimate of the locations of the target and the drones. If the sensor outputs are unavailable due to dropout, only the prediction is used. Next, the positions of the drones are updated so they surround the new target position. Then the process is repeated at the new position. The filter implements the TSOA multilateration method. This method was chosen as it is less vulnerable to noise when compared to the alternative TDOA method.

The filter was tested by simulating a target path and radar readings. Noise and dropout were added to the sensor inputs to test the filter's capabilities. It was found that the filter could successfully track a target moving at 4m/s when normally distributed noise with a mean amplitude of 1m was added to all sensor inputs. The filter could also handle a dropout in sensor readings from one drone for up to 5 seconds. The filter was designed so that swarm characteristics including following distance, sensor noise and iteration time could be easily changed as they become known.

The next major milestone for the project is to perform a practical test with one or two drones. This will occur over the mid-year break. Before this the Kalman Filter and multilateration algorithm must be incorporated into the work from last year's team. After the milestone I will add loss detection to the Kalman Filter and improve its response to real sensor noise from the drones. The project will culminate in a demonstration where the swarm will accurately track a target using emulated radar data.

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