# Object Tracking Using Drone Swarms

E25

**Academic Supervisor**

Richard Clare


**Student Name:**

Connor Terence O'Reilly

**Student ID Number:**

16987735

**Student Email:**

cor23@uclive.ac.nz

# Executive Summary

As discussed throughout this report and in many references, insect plethora and diversity are reducing. As discussed within the sustainability section, the world will benefit having an autonomous drone swarm tracking system. The autonomous drone (an unmanned aerial vehicle (**UAV**)) swarm should be proven to be capable of tracking a passive harmonic transponder attachable to most small animals, such as a snail. Upon proof of concept, the implications from real world implementation are highly beneficial and faster than current insect tracking methods. Tracking of invasive insects such the Vespa velutina or A. glabripennis enables quick hive eradication and prevention of further spread, along with extensive insect flight behaviour research possibilities that aren't currently possible. This project is important because proof of UAV swarm insect tracking concept is the first step toward a quick and reliable insect tracking technique discussed in project overview.

As mentioned in the project overview, the Wireless Research Centre (WRC) and Scion have sponsored design of a lightweight passive harmonic transponder. The passive harmonic transponder is attachable on small animals without restricting movement for many insects that are used to carrying weight as proven in [8]. WRC, Scion, and the department of forestry require proof of a UAV swarm tracking a passive harmonic transponder. This is because current tracking techniques, such used as part of [3] study, have many disadvantages discussed in the project overview.

Within the bounds of the scope the user requires a UAV swarm that: maintains a square base pyramid constellation, and centralizes directly above either an emulated target or a laptop broadcasting GPS coordinates. The project is divided into five problems that require solution, each team member contributes to an assigned solution and collaborates with others when necessary. All five problems are discussed within the project overview section. To summarize these: A vehicular Ad-hoc Network (VANET) allows for distributed computing, constellation formation, and radar data to operate as designed. Distributed computing and UAV constellation allows a multilateration algorithm to estimate the location of the emulated target. Radar data must be generated which gives the UAVs a trackable target. As the multilateration algorithm estimates the location of trackable target, the mothership UAV Intel NUC calculates desired GPS coordinates for all UAVs. The desired GPS coordinates achieve the UAV constellation forming a square base pyramid. The mothership sends packets containing the UAV desired GPS coordinates to each of the slave UAVs at the same time because of ZeroMQ communications architecture. Hazard avoidance is addressed by a group member and aligns with constellatory maintenance. The out-of-scope requirement is tacking a small insect.

All five group members have contributed amounts of progress. We have almost complete the UAV swarm formation project ahead of schedule. To specify: multilateration is predicted to work, the radar data generation and Kalman filter produce great data to emulate a trackable target, the VANET is established and UAV swarming logic is in the process of being optimized with data logging and hazard. Unfortunately, as mentioned in the unforeseen delay section, we have not been able to test much of our software which has restricted most progress to testing within a simulated environment.

My specialization in object tracking using drone swarms is the implementation of constellatory formation, maintenance, and movement implementing data collation. There are some vast improvements on software which are discussed in sections: theoretic designs and software development. The current software has been modified to collate data on UAV GPS coordinates (true and desired), multilateration output (target GPS coordinates), and log the swarming state along with any critical system errors; ultimately, allowing fine tuning of code and keeps record of all GPS coordinates as a practical system should. The final tasks that remain are to implement mothership-slave UAV dependencies, and ensure UAV Intel NUC software is in sync, implement a finite state machine on the mothership UAV to double check the UAV GPS coordinates and ensure the system is operating smoothly and according to design.

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# Project Overview

Large resource, collaboration, and specialized attention is performed for fruitful ecosystem research. Many academics, and their research point toward the requirement of more study; in particular, study of flying insects such as paths insects take when travelling from one place to another.

In 30 years, flying insect biomass has radically decreased by over two-thirds. As flying insect biomass has declined, the ecosystem has been affected. 80% of wild plants depend on insects for pollination; and 60% of avian species (birds) prey on insects as a primary dietary constituent. As less insects, such as honey bees, are available to pollinate wild plantation or exist as a food source to birds, we inevitably lose many wild plantation and bird population that are heavily reliant on insects for survivability. The affected insects play a huge role of essential ecosystem services (estimated at $57 billion per annum in the USA alone). Most importantly, the declination of insect biomass and the down-stream effects are getting worse and evidently more prominent. Hence, the increasing global efforts required to aid the restoration of ecosystem and improve sustainability. As in [1], [2], [3], [6], [14], [15].

A passive harmonic transponder (**PHT**) tag is attached on an insect and tracked with a radar system, as seen in [3], [5], and [8]; a PHT design has been sponsored by UC's Wireless Research Centre (**WRC**). Other techniques such as painting as in [17] don't provide data on the route an insect took from locations A to B, only that the insect travelled from A to B. PHT tags can only be carried by insects that frequently carry large weights, such as honey bees that carry pollen daily; but, with technological advancements the PHT is getting smaller and therefore lighter. Tracking techniques currently require a radar detection device set up close by (hand held or radar detection tower) using the radar system to track the PHT and therefore the location of the insect seen in [3], [7], and [8]. An alternative, cheaper approach is using a swarm of UAVs instead of devices described above. The use a drone swarms have many advantages over devices and techniques currently used. Namely, the UAVs will utilize radar system (telemetry) tracking of a PHT rather than pixel tracking used in mines or infrared to measure thermal differentials, as [18] explores. Radar tracking (telemetry) ultimately ignores most environmental clutter within woody / hilly areas during daylight seen in [4], [5], and [12]. Another advantage is the PHT does not require battery power and is very lightweight. The PHT is therefore mountable on small animals such as many scavenging insects, and in general a great design as discussed in [8]. The PHT tag absorbs then releases the wave energy and does not send a GPS coordinate; so, once lost recovery is difficult despite being inexpensive electronics. Furthermore, current tracking devices utilize visually pollutant radar towers, are highly expensive, require vast amounts of human time and resource to set up and use, cannot be built or operate in humanly non-accessible environments, and have greater difficulty gaining sustainability / environmental resource allocation consent. A swarm of UAVs will ultimately perform quicker and better tracking than the radar tower or a hand-held device, can operate at longer distances from headquarters, can track within non-accessible environments, is relatively inexpensive, and utilizes the same principles current devices (radar towers) use.

The Wireless Research Centre and other stakeholders such as the UC department of forestry and SCION have shared interest. The proof of concept of UAV swarm tracking is to achieve and prove the plausibility of small animal tracking via a swarm of UAVs centrally organized above the target. As previously discussed, there is growing ecosystem concern. There is increasing global demand of: biosecurity, management of destructive species, improvement of ecosystem sustainability, and more sustainable insect tracking techniques. The stakeholders above (any many others) require an autonomous drone swarm to help research, monitor, and investigate animal (insect) life. The drone swarm has 5 drones that form a constellation (such as a square base pyramid) as of Appendix A. The UAV swarm centralizes above and tracks a small moving object as depicted in Appendix B. The small moving object is free to move within 3D space, and movement is independent from the UAV swarm.

The UAV swarm proof of concept is required for reasons discussed above. This project follows on from previous year's work, a team of four. The software implemented by the four last year requires many improvements. UAV swarm formation is broken into manageable tasks, set as bullet points below:

- Multilateration: UAVs require target localization within 3D space (ability to find the target). The mothership UAV runs the software and outputs GPS coordinates of the target.
- Target tracking, radar data generation, and Karman filter: These take into consideration the systems non-linearity. Emulation of target / small animal to simulate and test UAV tracking.
- Drone Vehicular Ad-hoc Network (VANET) and transmission of data across a reliable wireless network. Enables formation, spread out computing, and radar data generation to operate.
- Swarm constellatory maintenance, movement, and data collation: software centralizes the UAV constellation above the target's GPS coordinates, and log all GPS-related data including multilateration output (the mothership UAV desired GPS coordinates) and system errors.
- Hazard identification: The drones are expensive assets and resource that require protocols for hazard avoidance, distance restraints, power and communication loss, and safe landing.

These solutions and manageable tasks are integrable components which have deadlines outlined in Appendix C. The completion of each task will bring each of us closer to a successful final year project.

A successful output is having concept proof. As we have progressed, vast amounts of efforts have gone into implementing each of the above bullet points. We are approaching the first of few remaining stepping stones to output a successful product as depicted in Appendix C. Ultimately, having an autonomously flying drone swarm that centralizes 10 meters above emulated (computer generated, not physically real) target coordinates, define some of the first few stepping stones of success. To have the UAVs centralize, and safely track an object such as a smaller drone or an emulated target is the ultimate goal and larger success of this final year project. Ultimate success would be implementing radio telemetry (radar systems), which is out-of-scope for this project.

To achieve a successful output, each of the components that fit together and achieve the stakeholders specified requirements must be achieved prior to final inspection. My duty is the fourth bullet point: I am responsible to implement precise and accurate constellatory maintenance centralizing above a target (all UAVs form a square base pyramid). The mothership UAV is above the square base, and is central. The idea is the mothership emits (sends out) a pulse of energy detectable by a radar system. The emitted pulse is sent toward the PHT (that's attached to an insect), which eventually stores the pulse energy and releases the energy a short time later. The energy emitted (released) from the PHT is detectable by radar systems, and is sent back toward the UAVs. The slave UAVs receive the signal at different times and therefore multilateration can be performed to locate the object (such as a PHT) as seen in Appendix $D_i$, and $D_{ii}$. Upon receiving the reflected energy pulse from the PHT, the slave UAVs send packets (information) to the mothership UAV. Once all packets are received by the mothership UAV from the slave UAVs, the mothership UAV performs multilateration and the algorithms output is the estimated GPS coordinates of the target. Tracking of an object is out-of-scope; instead, the UAVs must be able to track an emulated target path as briefly outlined in bullet points 1 and 2.

There are many problems the UAV swarm faces, and current software does not address all these problems. My intended solution is to address all problems within the scope of this project. All software to implement / that has already been implemented resolves the currently existing problems and are discussed in the progress to date section. The software aims to have the UAVs form a square base pyramid constellation that is periodically maintained, along with logging of all data at most efficient points within the software installed on the UAV. Upon completion of constellatory formation and maintenance, increases to software efficiency and addressal of out-of-scope problems follow.

# Progress to Date

## Overview

GPS module, Intel NUC and Pixhawk-series flight-controller are critical components to UAV centralization and constellatory maintenance; a process heavily reliant on GPS coordinates and accuracy, software efficiency, and data collation.

## My role: Constellatory formation and maintenance, and data collation (logging)

My role is to ensure all drones keep a square based pyramid swarm constellation. The constellation is to centralize above a target of interest such as a small animal (snail or insect), or an emulated target.

Milestone 0 was research into wireless drone communication, flight control software, communications and swarm logic software, the UAV specifications; along with research, test flight two UAVs and three simulated UAVs. Milestone 1(B) aims to fix bugs and flaws of software and successfully implement data logging, further improve drone swarm positioning, account for large higher-order derivatives and axial rotation around mothership (UAV GPS coordinate double check), perform numerous tests within simulated environment, and reinforce collaboration. Milestone 1(A) and 2 are not yet complete, so is a part of later sections.

## Background research

### Unmanned Aerial Vehicle (UAV)

The UAV is an asset to the WRC. The centralized mothership is very large in comparison to all four slave drones. The drones are indispensable and have many components. All components are non-specialized (buyable online e.g. from PBTech), and are critical to drone swarm formation. The UAV components are:

- A flight-controller, PX4 firmware installed onto Pixhawk-series flight-controller boards that enable autonomous flight control as part of [9].
- An Intel NUC Kit with 8$^{th}$ Generation Intel Core Processors. This can set up WiFi hotpots all UAVs use to communicate. This also executes essential software (such as multilateration) and therefore UAV instructions aside from that of the flight controller as with [10].
- A high-performance GPS module with proficient accuracy as specified in [11].
- ZeroMQ, enables fast communications. Forms an integral component the communications system. ZeroMQ provides functional operation within the multiple UAV swarming system sending packets from mothership to slave in one burst as with [16].

### *Intel NUC*

The Intel NUC and Pixhawk-series flight-controller runs software that ensures UAV constellatory maintenance. To locate and set the desired GPS coordinate, mothership and slave UAV Intel NUCs perform many operations. As multiple processes occur concurrently on the Intel NUC key specifications are: the number of cores, threads, and processor clocking frequency. There are 4 cores, 8 threads, and a maximum processor frequency just shy of 4 GHz. The Intel NUC is a great machine for this specific application because it allows for concurrent operation, allows for multithreaded algorithms, has low weight comparable to other computers, and has potential to generate WiFi hotspot.

### *PX4 / Pixhawk*

UAVs require flight-control without human input, Pixhawk-series flight-controller board with PX4 software achieves this. After the mothership's Intel NUC acquires information about the desired location (target GPS coordinates) the destination GPS coordinates get sent to a Pixhawk-series flight-controller to plot a new course. The mothership Pixhawk-series flight-controller controls the mothership UAV movement which in turn means GPS coordinates are dynamic and constantly changing. The mothership centralizes above the target within some given accuracy. At the same instance, the different slave UAV Pixhawk-series flight-controller controls movement of slave UAV. All four slave UAV Intel NUCs receive the GPS coordinates at roughly the same time because of ZeroMQ. The slave UAV desired GPS coordinate is sent to the flight-controller to plot a flight course. The slave drone moves to a target coordinate, which in turn forms the square base pyramid based off mothership UAV desired GPS coordinates. PX4 software determines flight-control of each drone. Modification to PX4 software was made as part of the previous group's work on software. Other aspects such as setting the orthogonally complementary GPS coordinate offset in meters (-5,-5), (5,-5), (-5,5), (5,5) based on mothership UAV, are performed as a series of instructions on the mothership Intel NUC.

### *GPS*

The GPS component is lightweight and has high accuracy. The slightest error in GPS coordinates could result in catastrophic failure, such as collision. The GPS component produces GPS samples quickly (more than 10 a second). The GPS can tolerate 4G acceleration, and can produce GPS coordinate samples at a velocity below 515 meters/second and allows for jerk of 20 meters/second^3. Other important specifications of the GPS module are temperature operating limits within range of operation, low power consumption, noise robustness, operating frequency, and high positional determination accuracy. All GPS specifications show sufficient operation for this project. A more accurate GPS may be required if inaccuracy becomes an issue. Though, if samples are taken at a high enough frequency, then GPS inaccuracy is mitigated due to standard deviation as of [22].

## Theoretical designs

Maintenance of constellation has many concurrent processes. The process is dependent on multilateration accuracy, VANET, and UAV swarming logic effectivity; the interconnected processes.

### *Mothership centralization*

The mothership UAV ultimately centralizes the UAV swarm above the target being tracked. Modifications to pre-existing software are part of multilateration, and using the same mothership UAV GPS coordinates through-out the software. Constellatory maintenance upon stationary and dynamic flight modes are reliant on mothership centralization. An area of acceptable slave UAV position is determined by an offset applied to the mothership's UAV GPS coordinates.

### *Slave drone arrangement*

Slave UAV Pixhawk-series flight-control and Intel NUC swarming logic software for positional control has not yet been fully implemented. ZeroMQ allows all slave UAVs to receive packets at roughly the same time (within an inaccuracy of one clock cycle, given UAVs are $5\sqrt{2} \pm 1\ m$ from mothership).

Slave UAVs run the same software that's prone to interrupts. The hardware / UAVs are operating in different environmental conditions, not truly equidistant from mothership and hence prone to becoming out of sync. Assuming multilateration uses the direct line-of-sight signal received, and the mothership generates a spherical pulse of energy at some time instance; the multilateration algorithm is unaffected from UAV out of sync software. A solution to minimize the effect of out of sync UAVs on UAV heading is implementation of a finite state machine operating on the mothership UAV. The finite state machine operates to update all UAV desired GPS coordinates, this is later double checked as briefly discussed in the area of acceptable location. The best implementation is to allow a finite state machine to update all UAV desired GPS coordinates every engineer designed time interval (such as 1 second, which is very long but used for illustration), and use the same mothership UAV desired GPS coordinates as reference for setting the offset of the mothership for slave UAV desired GPS coordinates.

All UAVs should have an orthogonally complementary geospatial arrangement of $5\sqrt{2}\ m$ (Pythagoras theorem) from the mothership. Mothership UAV centralizes the constellation and constantly receives packets from the slave UAVs. The packets the mothership UAV receives from slave UAVs include important data required for multilateration. After the multilateration algorithm produces an output of the target's estimated GPS coordinates, the UAVs continue normal operation until the engineer defined time instance is reached. Once the time instant is reached, new GPS coordinates are sent to the slave UAVs and this process iterates. To explain the highly complicated topic in three points: UAVs are constantly moving toward some set coordinates; the UAVs are continuously communicating information about current positions and multilateration data; the mothership UAV never communicates new coordinates to head to until we can reliably say that out of sync software will not cause any issues.

The slave UAVs set paths (offset from mothership UAV) to a location determined by multilateration algorithm. The path is only set every engineered amount of time because the coordinates are set upon completion of the sync-correcting finite state machine. The mothership UAV centralizes above the target being tracked. The mothership adds some 5 meter offset in both horizontal (x,y) dimensions and sends these offset GPS coordinates to each slave UAV. The slave UAV desired GPS coordinates are currently based on the GPS coordinates of the target being tracked. An alternative method is to set the new UAV desired GPS coordinates dependent on the mothership. These approaches have the same output GPS coordinates, yet have different consequences. Setting slave UAV desired GPS coordinates is implemented as a finite state machine. The finite state machine operates on the mothership Intel NUC. The alternative solution is preferable because as the target moves and new GPS coordinates are generated: If coordinates of target being tracked change during the process of updating the slave UAV desired GPS coordinates, then the base of the pyramid is no longer square and instead becomes trapezoidal. This in turn breaks constellation. To solve this, store a copy of the centralized mothership UAV desired GPS coordinates in memory registers. Set each slave UAV desired GPS coordinates dependent on the stored copy of mothership GPS coordinates saved in the memory register. Upon the engineered time interval, update the saved mothership GPS coordinates (**the coordinates of the target being tracked**) and set the new desired GPS coordinates for each drone.

Implementation via First-In First-Out (FIFO) buffer is another solution, although since the embedded system must operate in real-time this less practical.

### ***Drift from inertia***

A problem occurs when target changes direction too quick. Drones take time to stop and begin to move in another direction because of large inertial properties and the underactuated, abundant dynamic behaviour as discussed in [21]. By the time the UAVs begins to move in another direction, the target could leave the small radar range or have been overshot. The Kalman filter takes this into consideration with the emulated target engineered by Rowan.

Higher-order derivatives of an emulated target or insect determine amount of drift caused. Large changes of vectorized speed (velocity) in any direction cause UAV lag. Within a high-order differential system, and testing within a real-time environment, tracking of targets with smaller higher-order derivates is within the scope of this project. An example of this would be tracking snails or a slow emulated target. This allows the Intel NUC, GPS, and Pixhawk flight-controller to operate as a real-time embedded system and ensure drift is minimized prior to tracking faster animals.

### ***Rotational error and rotation around central axis***

UAVs that form the square base can rotate around a central axis increasing risk of two UAVs colliding. A solution to breaking constellation via rotational error is to use a finite state machine to double check if the UAV true GPS coordinates match the desired coordinates $\pm 0.1m$. The checking is unaffected from software sync because all UAVs are continuously sending and receiving packets.

Rotation of square base around a central axis also forms an area / imaginary circle / boundaries of acceptable localization for each point of the square base. In a practical setting, there are many trees; one solution such that tree collision is avoided while still tracking is to rotate around the centralized mothership GPS coordinates. Rotation around a central axis is to not limit / restrict UAV flight to translational movement / hazard avoidance, allowing also rotational movements / hazard avoidances.

### ***Area of acceptable location***

The area of acceptable location is a circle around the mothership. The circle forms two boundaries. If a slave UAV is too close to the mothership (within the circle) an error is generated to focus priority on shifting the UAV toward where it needs to be. On the other side, if a slave UAV is deviating outward and leaves the circle a different error is generated to focus priority on shifting the UAV inward. Ultimately, defining a smaller circle around the UAV desired GPS coordinates and making sure the UAV is within the smaller circle. A finite state machine of the mothership software effectively double checks UAV desired GPS coordinates and compares with the UAV true GPS coordinates; these ultimately lower multilateration inaccuracy, and ensures UAVs are where they need to be.

UAVs must prevent: rotational collision with an obstacle, or have an obstacle (tree) enter the inner circle area. Direct line of sight is required between slave UAV and mothership UAV, and direct line of sight between slave UAV and target being tracked. If direct line of sight is broken, UAVs don't send / receive data at sufficient rates. Although, direct line of sight can be broken, this should only occur for short amount of time and is only allowable if there's no alternative path that tracks the object.

## Simulations

Simulation has proven useful because target coordinates are logged and plotted. The simulation environment utilizes software GAZEBO and PX4. An image as of Appendix E is a snip of the GAZEBO and PX4 software running. All drones form and maintain a *flattened* square base pyramid constellatory arrangement. The GPS coordinates and position in the swarm are plotted as seen in Appendix F.

This proves all research accurate. The use of simulation is used to ensure modifications to existing code is applicable before performing a real flight test which ensures no bugs in code exist and means the drones are not at risk of collision.

## Software Development

### ***Data logging***

The past team only logged UAV desired GPS coordinates. Recent software developments logs UAV true GPS coordinates. This code has been implemented within the swarming logic python script. Upon update of UAV desired GPS coordinates, the true UAV GPS coordinates (along with time of update) are recorded to help with easy comparison between UAV desired and true GPS coordinates. Upon an error, the system shuts down; the swam changes "swarming state" and generates an error and UAV desired and true GPS coordinates are logged when the error occurs. Having the swarming state and error messages logged will prove beneficial in isolating any system errors or possible unwanted loss of drone.

Writing data to a file takes little time with efficient code and given Intel NUC specifications and processing power. To maximize data logging practical efficiency, other data in relation to setting (and logging) UAV desired and true GPS coordinates are logged during the same instance. Other data such as mothership multilateration output and tracking algorithm also require logging at the same instance of setting new destination GPS coordinates. The target being tracked GPS coordinates are from multilateration output (engineered by Oliver) / tracking algorithm (engineered by Rowan) which are compared. However, data is only logged every specified instance of time. For instance, all data is logged every 1 second (will be shorter). Logging of data at some specified period of time will allow fine tuning of system parameters such as the proportional-integral-derivative (PID) gains that are a part of flight-control. Different gains are required to track slower animals such as snails in comparison to track faster, flying animals such as an Asian hornet. Logs of all data allows for greater insight into system behaviour under different conditions, as well as keeping in mind that this project will inevitably track insects to learn about their behaviour and hence also has practical importance.

### *Mothership centralization and slave dependencies*

The software currently sets UAV desired GPS coordinates based on multilateration output. This solution has flaws because the target (eg insect) position will change while updating UAV desired GPS coordinates. This causes mean center error of the square base and hence the slave UAVs form a trapezoidal shape instead of a square. Untested software saves a copy of mothership UAV desired GPS coordinates to a memory register, then uses to calculate slave UAV desired GPS coordinates every engineer defined moment of time. Mothership UAV desired GPS coordinates updates upon setting slave UAV offset coordinates.

## Prototype development and results

### *Unforeseen delay*

To test any software and gain permission to fly the drones we require UC Senior Research Engineer Kelvin Barnsdale present because he has experience with the use of all drones the WRC has to offer. Unfortunately, Kelvin Barnsdale retired the start of this year though is hired to help with FYP work. As Kelvin Barnsdale began retirement, contact is difficult. This has caused delay with testing in the real world because we have not been able to perform a flight test with new software. As we have software ready to test, the unforeseen delay has restricted progress and further implementation in all fields. For instance, swarm maintenance and possible rotational error have not been fully observed in practice (we have flown the drones). There has also been restricted progress with swarm maintenance because we don’t truly know the cause of the errors that exist within the current software; namely, the errors that result in real-life setting are different to the errors that occur within the simulated environment. Even though there have been unforeseen delays, software is written and ready to practically test discussed in the software development section; software has proven effective in the simulated environment setting.

## Summary and conclusion of progress

The UAV swarm depends on Pixhawk-series flight-controller PX4 software to plot a path to the UAV desired GPS coordinates. The Intel NUC sets up a WiFi hotspot to communicate packets of information utilizing ZeroMQ. The mothership UAV performs multilateration with the data the slave UAVs collect. Multilateration estimates the target’s GPS coordinates for the mothership UAV to centralize above. The mothership and slave UAVs form a square based pyramid as a result, and the accuracy of the square base pyramid is not only dependent on the operating software but also the GPS module itself.

Unforeseen delays have restricted testing of software implementations to simulations. Despite the unforeseen delay, all tasks and milestones are on track for early completion. There are many tasks to complete that are in relation to the constellatory formation and maintenance of the square base pyramid. Tasks that require attention are: Improvement on mothership-slave UAV dependencies with sync correction, success of data collation, accountancy of large higher order derivatives and axial rotation about mothership GPS coordinates through GPS coordinate double checking for minimal error as depicted as a table within the Appendix C. The software is entirely implementable on the Intel NUC, and as mentioned the system should perform which high precision and accuracy. Ultimately, once we have regular access to flight tests progress will rapidly push onward.

Software developments to collate data of UAV desired and true GPS coordinates, multilateration data (which is also the UAV desired GPS coordinate / estimated emulated target position); as well as some improvements on UAV constellation formation are ready to test – although, some improvements await implementation. The entire system software is expected to have great functionality once fully complete; however, the system performance is limited by the drone because the system needs to operate in real-time and there’s evidently a lot to the system such as being an underactuated system with abundant dynamic behaviour. In spite of previous comment, system operation tracking an emulated or real target with low higher-order derivatives is more realistically possible given the systems properties and response times to correct errors in UAV true GPS to UAV desired GPS regardless of the PID control parameters.

# Remaining Milestones

This section is structured with sub-sections. All sub-sections have headings aligned with the assessment schedule. The assessment and due date are included in each heading on the next page. All assessments have tasks associated with the project, each milestone is briefly discussed and all tasks within each milestone are explained on the next page. Tasks are collaboratively set out as a table in Appendix C.

Before progress inspection is due (July 30th) the UAVs must accurately form a constellation and track an emulated path. As mentioned, the swarm forms a square based pyramid. Each group members contributions and specializations build the UAV tracking system. The constellation must maintain as a square based pyramid during both stationary and dynamic flight (at all time), and must exit autonomous flight upon hazard identification. All UAVs (the drone swarm) will follow an emulated target by calculating ranges via multilateration. The mothership UAV centralizes above the emulated target path and defines the basis for all slave UAV desired GPS coordinates which maintain the orthogonally complementary square base of the pyramid.

As a practical requirement, the UAV swarm must *also* log all UAV desired GPS coordinates, all UAV true GPS coordinates, multilateration output (the GPS coordinates of the target), emulated target GPS coordinates path, along with any critical system errors associated with breaking of constellation.

Overall, all project milestones intend to be complete before progress inspection. After progress inspection, and assuming all milestones are finished, we have the option to move into out-of-scope project tasks. The tasks that are out-of-scope are to implement radio telegraphic tracking of a passive harmonic transponder that attaches to small, slow moving animals such as snails. However, as mentioned this is out-of-scope and will require further research – a reason behind finishing early.

## Tasks

### *Data collation & UAV coordinate dependencies*

Data collation (logging) and UAV coordinate dependencies are close to completion. Simulations and flight tests will enable fine tuning of the software, and logging of data; this will be implemented alongside the constraints set out by computer engineer specialist Nicolas. The aim is to ensure these are up to standard and collate accurate data efficiently without impacting system performance.

### *Account for drift*

Test flight with a slow-moving emulated path which minimizes the higher-order derivatives and eliminate drift allowing fine tuning of multilateration and hazard avoidance.

Increasing the potential for higher-order derivatives to emulate fast moving objects becomes a problem, software to account for these is within the Kalman filter engineered by Rowan.

### *Rotation about central axis*

As mentioned, this means the UAV swarm is not limited to translational movements. Rotation about a central axis governed by the centralized mothership UAV GPS coordinates is primarily used for hazard avoidance and correcting unwanted rotational deviation. The solution and software to this will be complete along-side the hazard / obstacle avoidance engineer Alex.

### *Area of acceptable location*

The areas of acceptable location define a range of GPS coordinates the UAVs must exist within the boundaries of. A finite state machine is used to cycle through and check that the UAVs are within the specified boundaries. Implementation of this is somewhat along-side the hazard / obstacle avoidance engineer Alex.

## Assessment schedule

### Progress Inspection [July $30^{th}$]

The purpose of this stage is namely to summarize months of work into a 10-minute oral presentation. As mentioned above, by the time of progress inspection the drone swarm must form and maintain the square base pyramid constellation. Upon target change of direction, UAV inertial drift must be minimized to enable smooth tracking of small animals.

The primary goal by this time is to have the scope of the project almost entirely complete.

### Final Inspection [September $24^{th}$]

The purpose of this stage is similar to the purpose of the progress inspection.

As we aim to have complete the project before progress inspection, any work after this time is out-of-scope and software improvements. This includes accounting for drift, rotational error, constellatory rotation around central axis defined by centralized mothership.

### Poster & Oral Presentation [October $8^{th}$]

The purpose of this stage is for the sponsors (WRC) and public showcase.

All work complete as part of final inspection is essentially required to be set out and displayed in presentable format. Setting the years work in presentable format is preliminary to design of poster and oral presentation.

### Meetings & Project Handover [October $15^{th}$]

The purpose of this stage is to hand over all documented minutes, conclude all work complete for sponsor each week to keep the client informed on project progress, as part of early professional engineering experience in the workplace setting. Meetings continue through semester 2.

### Final Report [October $22^{nd}$]

The purpose of this stage is to have a write a document that contains all progress.

The content of the Assessment schedule section is better set out as a table depicted in Appendix C.

# Sustainability Analysis

Triple bottom line analysis assesses societal, environmental, and economic indicators which provide professional engineers insight into the project sustainability. The greater the positive implications (compared to negative) a project has on the environment, society, and economy are factors which ultimately determine the sustainability namely with younger generations in mind.

As mentioned in prior sections, insect biomass is declining and becoming more evident and worse each decade. More investigations and greater measures must be carried out to counter-act the decline. For instance, USA plans to eradicate Asian hornets. UAV swarm tracking of insects would advance research and rate of data collation into insect behaviour as established in project overview and [12], especially with 5G developments progressing. Research with greater efficiency and yield allows investigators to quickly locate, and understand the pattern of behaviour of sources that cause the reduction of insect abundance and diversity. In spite of the benefit UAV swarm tracking provides, there are negative impacts to consider which weigh against all the plausible benefits.

## Triple bottom line analysis

### *Environmental indicators*

The environmental impact UAV tracking provides is huge and has downstream affects – as with [1], insects (both beneficial and harmful) influence plant and animal life. In turn, impacting the economy and societal views in both positive and negative manners.

As of [3], the V. velutina (Asian hornet) is an invasive insect indigenous to South-East Asia. The Asian hornet has spread to other continents and inflicts disability-adjusted life year (DALY), death, and are particularly decimating honey bee populations. As part of an environmental indicator, increased biosecurity of beneficial insects such as honey bees can result from the UAV swarm tracking system. The UAV swarm helps locate Asian hornet hives, and applicable to other insects allowing study of insect behaviour. As of [13], UAVs are quiet and can operate at high altitude; animals such as live stock or wild life are unaffected. UAVs compared to radio towers or hand-held devices have relatively little disturbance on live-stock or wild life. As of [14], insects such as A. glabripennis infest trees. These trees are felled and possibly get transported overseas. The A. glabripennis then leaves the transported wood to form a new nest, travelling up to 50 km. The infested tree is later felled and the cycle repeats. The A. glabripennis is trappable with pheromone traps. Attachment of lightweight PHT and tracking the A. glabripennis back allows quick hive eradication, in turn lowers further outbreak which is important because this insect is capable of destroying above 30% of urban trees as of [20]. UAV tracking improves study of flying insect behaviour and improved life biosecurity.

UAV tracking has vast potential to improve wellbeing of people and communities enabling social, economic, and cultural wellbeing advancements. UAV tracking allows improved biosecurity, biological control, surveillance and diagnostics which in turn help sustain natural and physical resources in terms of the foreseeable needs of future generations. An example of this is above and discussed within [14]. Life supporting capacity of ecosystems is improved, explained within [1], [2], and [14] in spite of elimination of destructive insects. And, the purpose of the UAV tracking system discussed in project overview section aims to provide remediation, and mitigation of the damaging effects of small insects such as A. glabripennis or V. velutina. As briefly mentioned, the UAV tracking system is not only applicable to destructive insects. UAV tracking system also has potential to track birds, or scavenging insects such as honey bees due to the versatility and relatively lightweight UAV and PHT technology; especially in comparison to other tracking techniques such as radio towers or hand-held devices. Ultimately, the UAV tracking system has great potential and vast environmental sustainability according to the Resource Management Act promoting sustainable management of natural and physical resources.

Environmental Impact Assessment gives insight to biological, physical, and chemical indicators. The UAV tracking system has minimal noise, and no immediately damaging effect on the ecosystem or life-supporting capacities such as air, water, or soil, nor any immediately damaging effects in terms of chemical pollutants. Life Cycle Analysis follows: prior to manufacture of UAV components, materials are extracted. The materials are lightweight and require multiple processes to produce the plastics, carbon fiber, and electronics. The extraction, manufacture / assembly, and distribution methods depend on the corporate entity which design the UAVs, such as 3DRobotics. Extraction and manufacture stages are most damaging. Many UAVs have replaceable components increasing product life span. Furthermore, the end-of-life product is recyclable. The environmental damage the UAV tracking system is minimal during product-use stage. The PHT is lightweight and has does not weigh down larger insects such as the Asian hornet or honey bees as [3], [4], [7], [8] prove. UAVs are battery powered, requiring little charge meaning the only carbon emissions is from the power grid.

## ***Societal sustainability***

Analysis of societal sustainability requires knowledge of the stakeholders. Assessment of many societal aspects are considered. The societal sustainability is set out as bullet points for easy reading:

- WRC, Scion: there's primary interest in biological control, risk assessment, biosecurity, surveillance, diagnostics, biodiversity, and ecosystem function. WRC, Scion, and department of forestry share the same interest. The UAV swarm tracking proves societal sustainability.
- Manufacturers: For societal sustainability, manufacturers need generally recognized cohesion and services, beliefs shared with the public, understanding and sympathy toward the public and environment, personal and property rights, and share fears and aspirations with society.
- Conservationist: Would agree to allow insect tracking, however if and only if the underlying morals and principles of the two stakeholders above coexist with the conservationist.
- Land owners: As with environmental sustainability and [13], yet independent from the section itself, almost no negative effects on land owners besides privacy concern.
- Government and general public: As with above bullet points, there is societal sustainability. Namely since the outcome of this project intends only positive intentional and unintentional social consequences and hence the societal sustainability.
- Business (e.g. honey industry): There is a healthier biophysical environment for workers reducing DALYs. The health and safety improvements align with societal sustainability.

## ***Economic impact***

As with [1], insects currently provide USA ecosystem services estimated $57 billion USD per annum. The lower insect abundance results in greater investment from businesses and governments to compensate. Improved biosecurity and biological control through replenishing environmental losses and social sustainability maintenance, investment in UAV insect tracking is comparably minimal with respect to ecosystem damages. Economic impact in the USA due to invasive insects costs $70 billion USD per annum as of [15]. Furthermore, the A. glabripennis has potential to destroy above 30% of urban trees as of [20]; a loss of $669 billion USD in the USA. UAV tracking of invasive species such as the Asian hornet or A. glabripennis would have great economic benefit and sustainability. The cost of UAV tracking system is less than the cost of damages an invasive species inflicts. In comparison to current methods (radio towers) which require rebuilding every use; the UAV swarm tracking system is comparably much cheaper, can access more environments than the radio towers and people, consent of resource allocation is easier, is less visually polluting, and is quick to locate (beneficial or invasive) insect hives. Hence, the far superior economic sustainability UAV insect tracking systems provide in comparison to conventional insect tracking techniques.

# Conclusion

Investigation and proof of concept of UAV swarm tracking of insects / emulated targets is a great step toward better biosecurity and ecosystem stability. As insect plethora and diversity is declining, newer and faster approaches to insect tracking are required to enable greater research into insect behaviour and hive identification. Current techniques are inefficient, cannot operate in environments non-accessible to humans, harder to gain resource allocations, and therefore many disadvantages in comparison to UAV swarm tracking of insects such as the techniques used in [3]. UAV swarms form a square base pyramid constellation centralizing above a target, and follow the target; this does not limit the tracking to a specific area as radar towers are, has minimal effects on many stakeholders as discussed in [13], is environmentally friendly and therefore resource allocation is a guarantee in comparison to building a radio tower, and improves health and safety as discussed in the sustainability section, along with many more advantages discussed throughout this report. UAV swarm insect tracking is highly advantageous in comparison to current techniques. Hence, proof of concept is required sooner rather than later due to the radically declining insect population (such as honey bee population decline as a result of Asian hornet invasion) as discussed in the sustainability section.

UAVs have many components which enable constellatory formation and maintenance. Pixhawk-series flight-controller plot a path the UAV takes to arrive at desired GPS coordinates determined via multilateration of all slave UAVs. The Intel NUC runs software designed to determine all UAV desired GPS coordinates that depend on the multilateration output performed on the mothership UAV. All slave UAV desired GPS coordinates are determined dependent on the same mothership UAV desired GPS coordinates as discussed in the theoretical designs and software development sections. The GPS modules have high performance, and tolerate the higher-order derivatives generated by the UAV. The ZeroMQ architecture, briefly discussed in the background research section, enables fast and efficient communications between all UAVs. All UAV system specifications have high performing parameters and should yield accurate results.

Software improvements and research were primary tasks finished prior to progress inspection. Outside of constellatory maintenance, multilateration and target emulation software was improved and have been tested in simulated environment although have not been tested in real-time flight experiments as mentioned in prototype development and results and simulations. Data logging and mothership-slave UAV dependency software test ready and improvable. Mothership UAV centralizes above emulated target, and slave UAVs below form a square around the mothership UAV GPS coordinates; all this is logged and able to read. The mothership UAV desired GPS coordinates are determined from multilateration. All data and critical errors log because this in turn allows us to read and determine system performance and any required fine tuning of software; furthermore, keeps logs of all UAV movements and therefore the movement of a target. Early completion of project is expected and progress on out-of-scope work follows requiring additional research and software adaptions.

Triple bottom line analysis has proven the UAV swarm as a sustainable project. Potential uses such as tracking of Vespa velutina or A. glabripennis has many beneficial outcomes and little negative outcomes, where most negative outcomes from UAV swarm tracking of insects are not directly caused by the UAV swarm. As mentioned in the life cycle analysis in the sustainability section, the sustainability of UAV swarm tracking of small animals such as insects is largely influenced by the UAV manufacturers. Regardless of the potential damages the manufacturers cause, the vast impact on environmental, societal, and economical is proven sustainable and highly beneficial via Resource Management Act and Environmental Impact Assessment (such as the brief product life cycle assessment), stakeholder investigation, and has vast potential to reduce economic loss as a result of destructive insect infestation.

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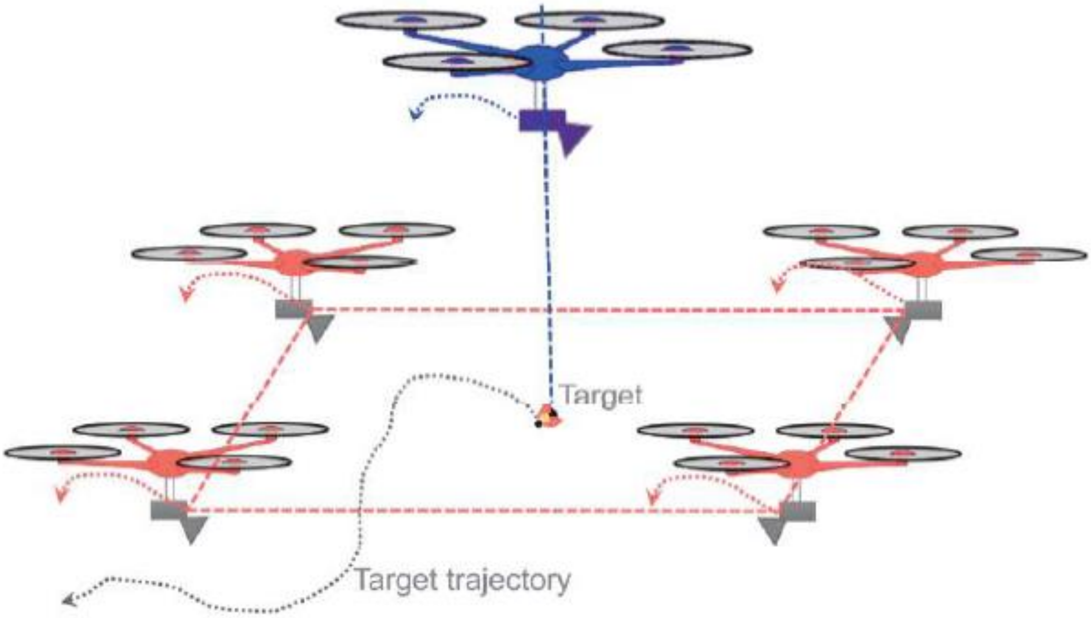
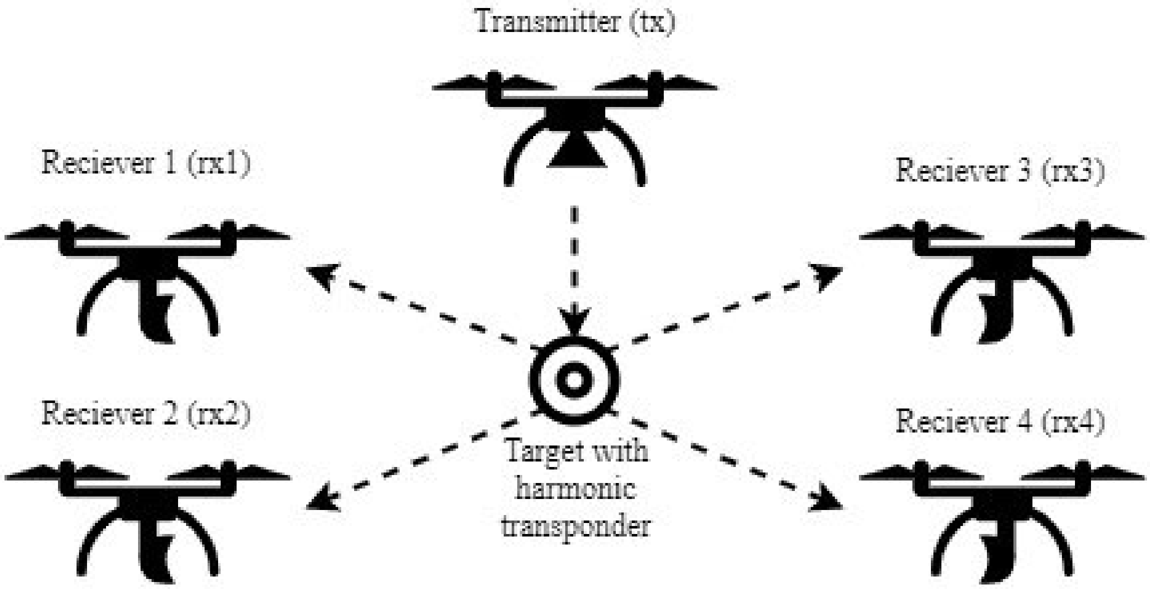
# Appendix



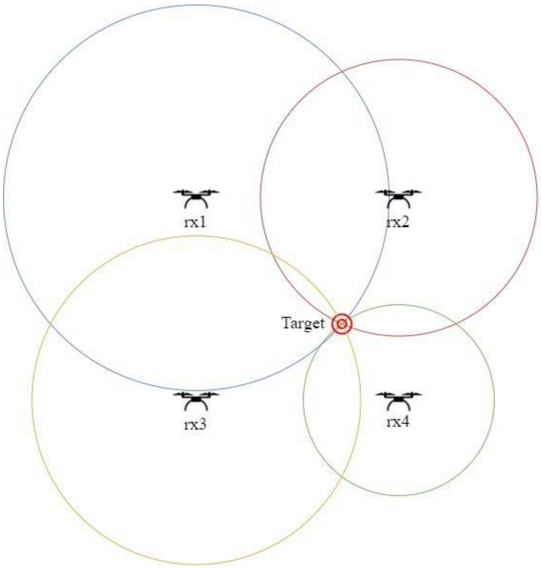

*Appendix A: UAV Swarm*



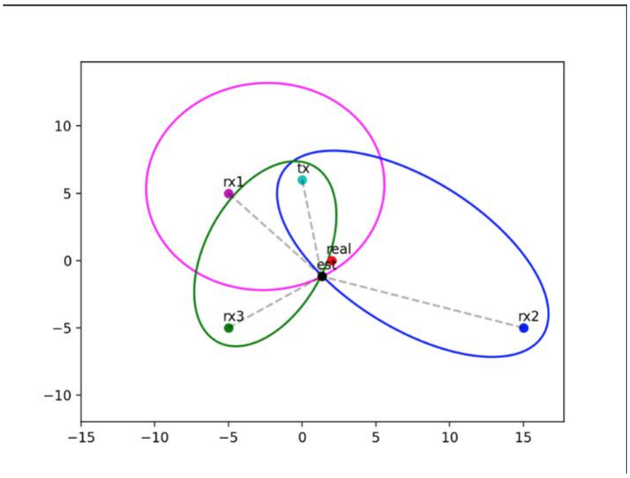

*Appendix B:* UAV arrangement

| 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. Success of data collation. |
| 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 (inertia / drift). Axial rotation around mothership. UAV GPS coordinate double check |
| 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** | | | | | |

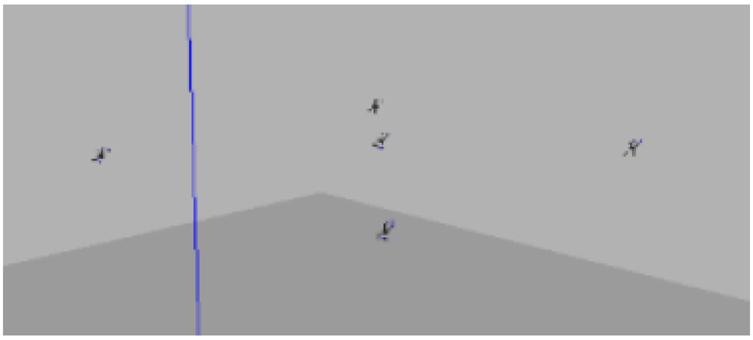
*Appendix C: Remaining Milestones*



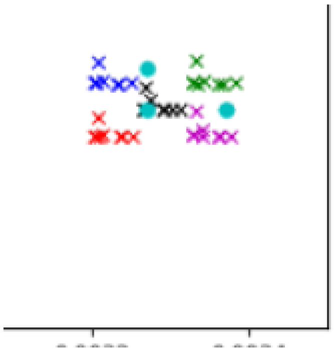

*Appendix $D_i$: Multilateration birds eye view*




*Appendix $D_{ii}$: Multilateration 3D space*



*Appendix E: Simulated Environment*



*Appendix F: GPS target coordinates plot with multilateration output*

## Progress Report Marking Sheet

**Project Name:** E25: Object Tracking using Drone Swarms

**Student Name:** Connor Terence O'Reilly

## All Individual Marks

| Item | Weight | Mark out of 100 |
|---|---|---|
| Executive summary | 15 | |
| Project overview | 10 | |
| Progress to date | 30 | |
| Remaining tasks | 10 | |
| Sustainability analysis | 10 | |
| Conclusions | 15 | |
| References/support | 10 | |
| **Total weight** | 100 | |