Drone-based Aerial Release Mechanism for Mosquitoes

COMBATING ZIKA AND FUTURE THREATS
A GRAND CHALLENGE FOR DEVELOPMENT

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1 Introduction

Mosquitos are one of the world's deadliest disease vectors, responsible for millions of deaths every year. More specifically, the *Aedes Aegypti* mosquito spreads dengue, chikungunya, zika and yellow fever viruses, and is present in tropical climates worldwide.

Current control techniques using insecticides or fumigation are limited in effectiveness due to the need for constant re-application and have negative effects on the environment. Several genetic techniques show promise in the control of their population, including gene drive, *Wolbachia*-based techniques and the Sterile Insect Technique (SIT). Among these, SIT is one of the most well-understood, having been used successfully for other insects for decades. SIT suppresses the population of an insect by flooding the local population with sterile male insects that mate with the local females after competing with wild males, producing sterile eggs that do not hatch.

SIT works when an entire insect population is regularly flooded with sterile males, often with a factor of 10 or even more sterile males for each non-sterile local insect. These sterile insects must be mass-reared, sterilized and then released regularly throughout an infested area, often weekly through areas that can cover hundreds of hectares. Mass-rearing techniques have been developed for *Aedes aegypti*, but current release techniques for mosquitoes are often limited due to several factors:

- Once released, *Aedes* mosquitoes travel very little from the release point - often less than 50m during their entire lifetime
- Roads are not always available or easily accessible in release areas
- Ground-based release using vehicles is very time-consuming and people-intensive

In order to scale up the release of sterile mosquitoes beyond laboratory tests and into a suppression campaign, a new release technique is required. Existing techniques to release other pests using airplane-mounted mechanisms, in particular the Mediterranean Fruit Fly, suggest that aerial release has potential to scale up mosquito release as well. Recent advances in drone technology, as well as initial investigations by the Joint IAEA (International Atomic Energy Agency) - FAO (Food and Agriculture Organization) Insect Pest Control Laboratory (IPCL), have contributed to the design of this project.

This report details the design, lab testing and field validation of a drone-based Aerial Mosquito Release Mechanism. Lab tests are first performed on mosquitoes to gauge their resistance to chilling, compaction, wake up times and damage to mechanical handling. These inputs are then used to design the mechanism, with further tests in the lab used to measure its efficacy in releasing mosquitoes and preventing excessive damage. The mechanism is then validated through field tests using several hundred thousand mosquitoes. Lessons learned are then presented that will guide further design of the mechanism.

Figure: The Aerial Mosquito Release Mechanism, mounted underneath a drone and waiting for a canister of mosquitoes before a mosquito release flight in Brazil

2 Defining mosquito release mechanism parameters

In order to extract and define requirements for the aerial release mechanism, we needed to investigate multiple factors and their impact upon mosquito quality. For instance, to what extent can mosquitoes be packed and stored in a small volume without damaging the mosquitoes at the bottom of the pile? At what temperatures is it best to store mosquitoes? At what flight altitude should the drone be flying such that mosquitoes have enough time to wake up and do not fall on the ground?

To answer these questions, we have been running rigorous lab tests to assess the effect of cooling, compaction and wind resistance in relation to the subsequent impact upon sterile male quality. Some of the key findings are highlighted in this section.

2.1 Initial design parameters

Mosquito populations can vary widely based on climate, local human population and other environmental factors. The typical capacity of a mass-rearing facility designed for a pilot trial is around ~1 million sterile male mosquitoes per week. As an initial goal, the release mechanism should be able to transport and release between **50,000 and 100,000** in a single flight, thus releasing all produced mosquitoes in 10-20 flights every work-week, or 2-4 flights per day.

In a typical SIT campaign we expect to release between 2,000 and 6,000 mosquitoes per hectare in order to successfully suppress the local population. Given the above target capacity per flight, the drone-based system should be able to fly and release over an area of **at least 8 hectares** (50,000 mosquitoes at 6,000 per hectare) but ideally **up to 50 hectares** (100,000 mosquitoes at 2,000 per hectare).

In order to release tens of thousands of mosquitoes in a single drone flight, the mosquitoes must be compacted into a small area, transported to the release site, and loaded into the mechanism before release. Tightly-packed adult mosquitoes quickly damage each other if stored in too small of a container. Chilling mosquitoes to a low temperature puts them into a lethargic “sleep” state from which they can fully recover once the temperature rises again, and is thus the preferred way of preparing and transporting mosquitoes for aerial release.

Several flights are possible per day, so the mosquitoes should be split and stored in **separate temperature-controlled canisters** that can be loaded into the mechanism individually.

2.2 Storage/transport temperature of mosquitoes

2.2.1 Ideal storage temperature

Chilling mosquitoes is the only way to compact them enough for transportation in large quantities. Chilling them to too low of a temperature can damage them, reducing their fitness upon wakeup, or even kill them. Above a certain temperature, however, the mosquitoes begin to wake up and be active. If this occurs while they are compacted for transport they begin to move around, damaging their neighbours and themselves, once again reducing their fitness. A specific temperature range must thus be determined in which mosquitoes can safely be stored. An initial literature review presents a safe temperature between 6 and 10 °C.

2.2.2 Wake up time following immobilisation

In order to determine the height at which the drone will conduct an aerial release, it is important to know how long the sterile mosquitoes will need to "wake up" following immobilisation for **x** amount of time at **y** temperature. Thus, we conducted an experiment at 3 temperatures across our range that we will aim to store the mosquitoes during transport and release and for different lengths of time in order to ascertain how long it takes them to recover and regain the muscle activity necessary to fly. Results are detailed below in the chart. 2 repetitions were taken and an average calculated for each temperature and duration. It was interesting to note the large jump in time taken to recover when the temperature drops from 8 to 6 °C. Thus, based on this result we further narrowed down the temperature range that we will aim to store the adults between 7 and 10 °C.

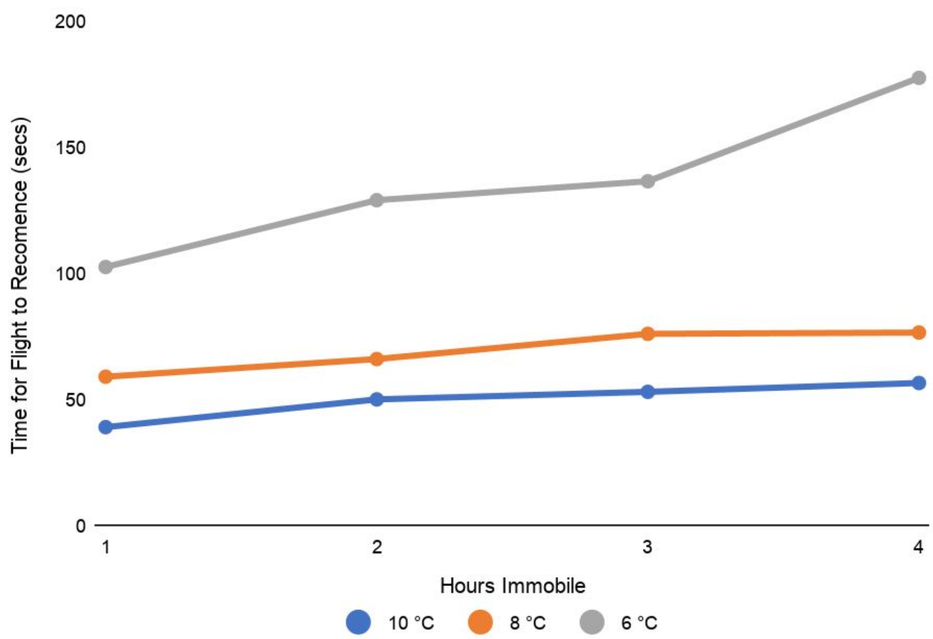


Figure: The time taken in secs for adult male mosquitoes to regain the ability to fly after a period of immobilisation from between 1 to 4 hours at 6, 8 and 10 °C

2.3 Maximum level of compaction

As the amount of mosquitoes packed into a canister increases, the mosquitoes at the bottom of the canister are subjected to increased weight due to their fellow mosquitoes above them. In order to determine the maximum height and thus the capacity of the storage container, we need to determine how much weight a chilled mosquito can handle without a significant amount of damage.

We performed a test in which adult males were subject to varying weights held above them while in a chilled and immobile state – as per transport to the field site and eventual release conditions. As mosquitoes are very light and due to space restrictions (rearing the quantities of adult males to equate to the weights required to be tested would not be feasible/possible), we used our substitute particle (cumin) to serve as immobile mosquitoes. Cumin was weighed and wrapped in mesh nets and secured closed prior to being placed upon the immobile adults and held there for a period of one hour. Following this, the adult mosquitoes were flight tested to measure their quality following varying levels of compaction at 0 g (controls), 25 g, 50 g and 75 g. Individuals were also visually inspected under a stereomicroscope to look for missing limbs or damage to wings that would prevent flight from occurring, with results detailed below:

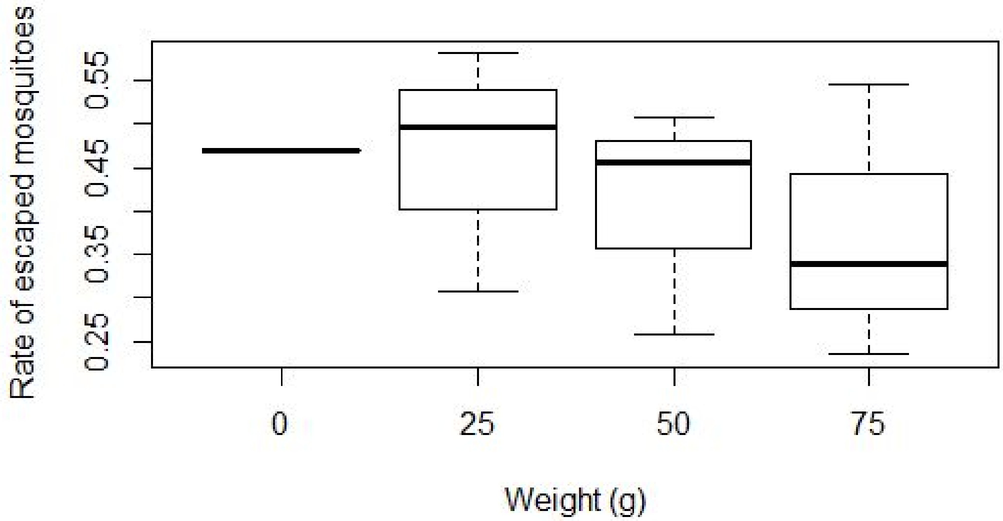


Figure: The % of adult mosquitoes who were able to successfully pass the flight ability test after 1 hour of compaction under different weights

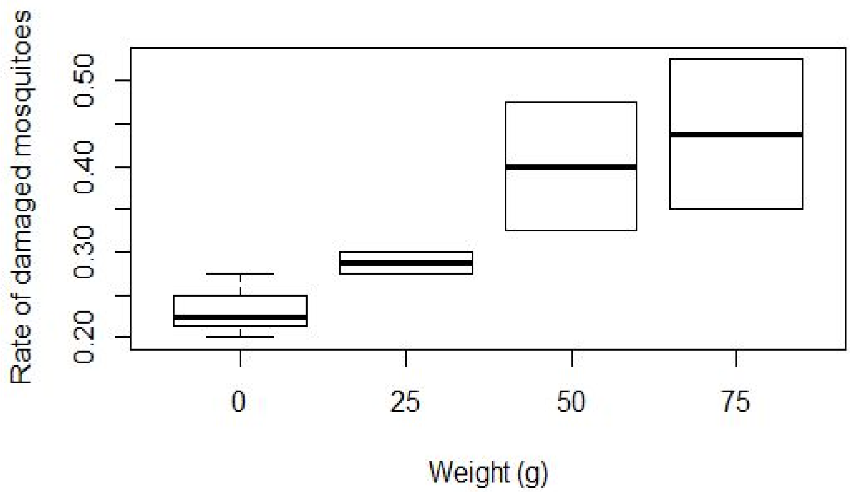


Figure: The % of adult mosquitoes who were classed as “damaged” following 1 hour of compaction under different weights

Results showed, that even with a weight equivalent to 25 g of mosquitoes, the damage to the adults underneath was already becoming significant. **This equates to a maximum canister height of only 5 cm**.

As this dimension is very restricting, to further validate these results we repeated the test with actual mosquitoes instead of cumin. We constructed a tube with holes cut at intervals of 1 cm and filled it with immobile adults. After leaving them inside for two hours, we then took samples across a range of heights and monitored their subsequent survival and flight ability. As expected, the results were the same (see below) with a dramatic impact seen when the height of the column of mosquitoes was above 5 cm.

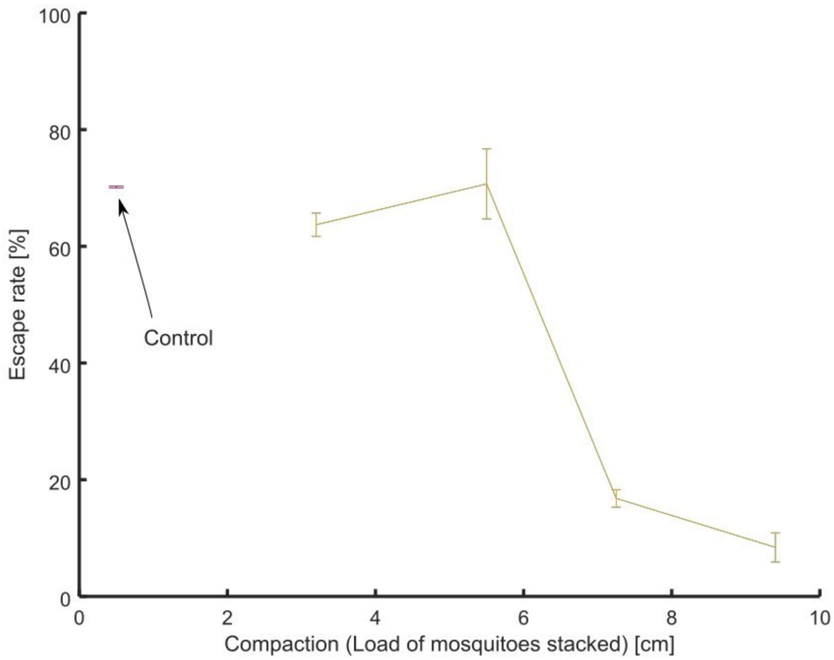


Figure: Escape rate of mosquitoes that were compacted, compared to control group

2.4 Drop speed of mosquitoes

Another factor in determining the altitude at which mosquitoes are to be released is the speed at which they typically fall. To investigate this, we implemented a video capture set, which comprises a high performance industrial video camera (IDS camera), a metric ribbon resting on the wall (2 meters in length), and a white led light high power focus (40W). For the analysis, we used different mosquito specimens, all of type *Aedes aegypti*, which had previously been frozen to kill them. We selected three different individuals that showed small differences in size.

Based on our experiments, we found that the maximum free fall speed of a mosquito (*Aedes aegypti*) in a closed space would have a near upper limit of about 2.5m/s, which ensures a minimum falling time of 40s at a 100m dropping height. Due to the speed of the drone and climatic conditions, this falling time should be higher in a real scenario.
Hence, assuming a wakeup time of the mosquitoes around 50 seconds (see previous section), a flight altitude of 100m seems reasonable.

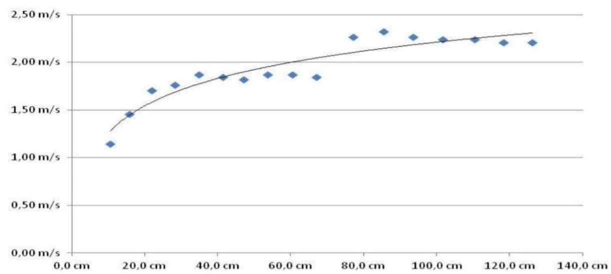


Fig. 2 Free fall Speed results for individual 1 (biggest size)

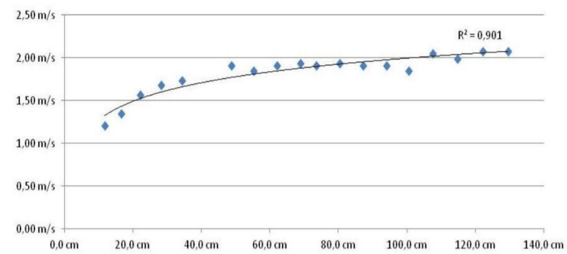


Fig. 3 Free fall Speed results for individual 2 (medium size)

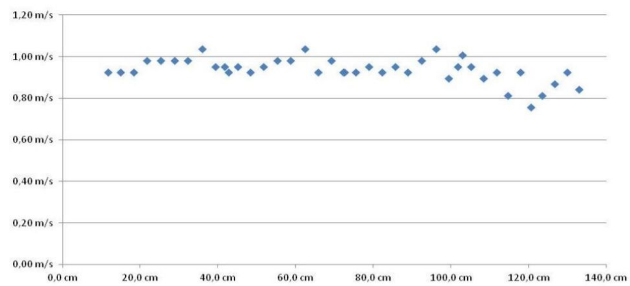


Fig. 4 Free fall Speed results for individual 3 (smallest size)

Figure: Free-fall speeds over time of mosquitoes of varying sizes

2.5 Wind resistance test

We measured the effect of wind on sterile male mosquitoes in order to determine whether there is any limitation on the maximum tolerable wind speed mosquitoes can endure without being damaged. Wind can be generated by the movement of the drone or weather conditions. The experiment was carried out with different wind speeds in a wind tunnel and the flight ability of the mosquitoes subsequently measured for each.

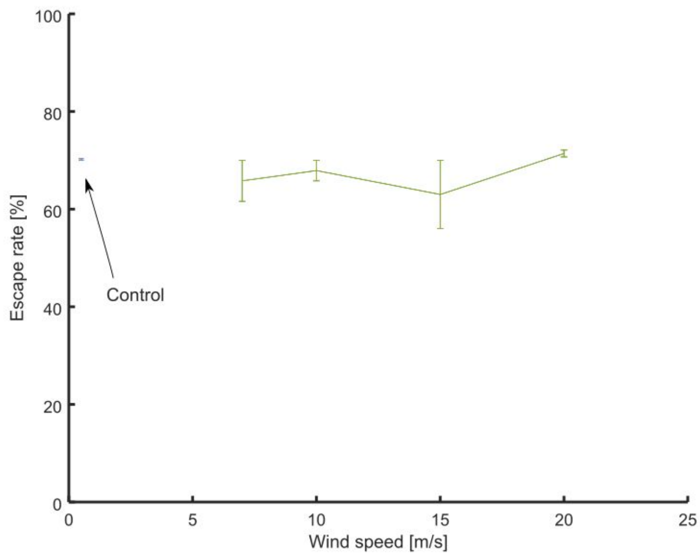


Figure: Escape rate of mosquitoes release into an airstream of varying speed, compared to a control group

We found that mosquitoes are extremely resistant to wind, with a survival rate above 90% for all measured wind speeds. From this we conclude that strong winds, especially due to the high velocity of the drone, does not critically damage or affect the mosquito quality.

2.6 Summary

The following table summarizes the results of mosquito-based tests that inform the design of the mechanism:

Mosquito Release Mechanism Parameters	
Canister capacity	50’000 mosquitoes
Storage temperature range	7 - 10 °C
Maximum canister height	5 cm
Target release rate	2,000 to 6,000 mosquitoes per hectare
Mosquito free fall speed	2.5 m/s
Target release altitude	100 m
Flight speed limitation	None (based on wind tests)

3 Aerial release mechanism design

Based on the defined and identified criteria in the previous section, we designed a release mechanism including mechanics, electronics and software. The mechanism mounts on a drone and enables aerial release of mosquitoes. In this section, we briefly review the latest design with all its features as well as how we tested and calibrated the system.

3.1 Release mechanism

The main parts of the release mechanism are: (1) storage unit consisting of a canister that keeps mosquitoes at cold temperatures surrounded by isolation, (2) an ejection mechanism featuring a rotating cylinder that brings mosquitoes from the storing canister to the outside, (3) a release area where mosquitoes fall onto and then slowly enter the wide open, (4) onboard electronics featuring sensors and cameras to control and monitor the state of the mechanism and mosquitoes.

1) Storage unit or Canister: we designed the holding canister to fit 50’000 mosquitoes inside. In order to keep the insects at the target temperatures, we put phase change materials (PCM) with a target temperature of 4 deg Celsius in the canister walls. The canister is placed in an insulation box made of styrofoam to minimize heat exchange. The whole storage unit featuring the canister and insulation box can then be loaded into the ejection unit. This enables us to load the release mechanism multiple times while in the field without the need to remove any parts from the drone.

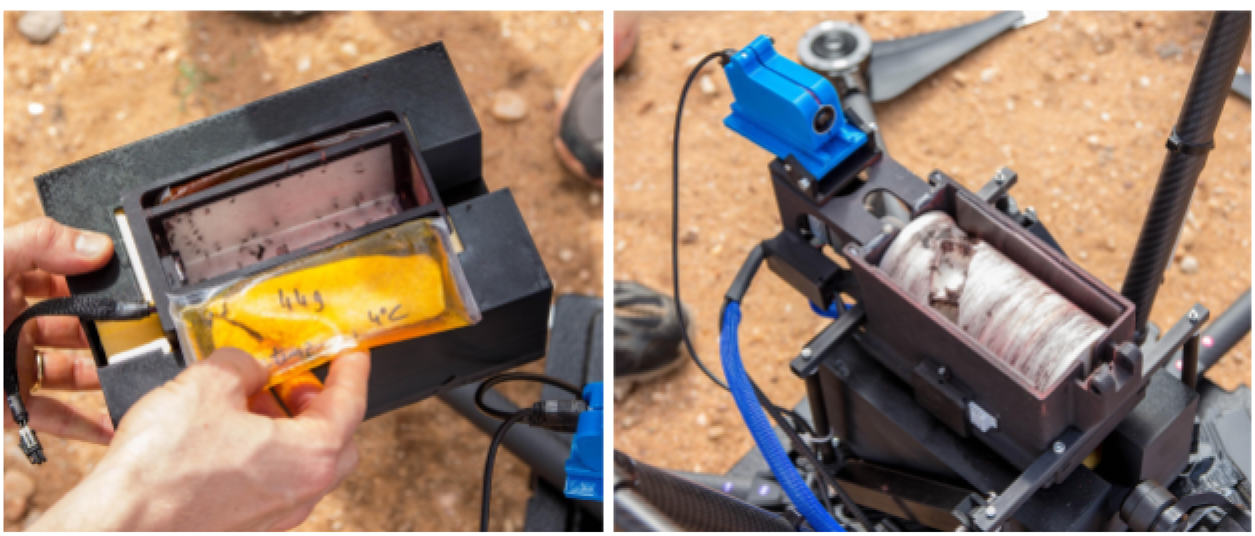


Figure: The canister (left), surrounded by isolation and with a PCM pack in half-frozen state. The mechanism (right), seen upside-down with the release monitoring camera (blue)

2) Ejection Mechanism: the ejection mechanism consists of a rotating cylinder connected to a stepper motor embedded in a structure. This mechanism was developed for other fragile insects within the ERC REVOLINC project (PCT/EP2017/059832). The cylinder has 6 discrete holes that each can take up around 800 mosquitoes. Hence a full cylinder turn should release around 5,000 mosquitoes. The stepper motor controls the rotation of the cylinder with high accuracy and high torque. The motor can be set to various speeds; we found that values between 1-3 RPM are optimal, leading to release rates of 5,000-15,000 mosquitoes per minute. The structure around the cylinder is built to minimize airflow from the outside to the inside of the canister. In addition, the connection between cylinder and structure is designed in such a way that it is easy to remove the cylinder for cleaning.

3) Release area: the release area is simply an inclined surface where mosquitoes fall onto after transportation through the cylinder. While the cylinder ejects discrete amounts of mosquitoes, the airflow through the release area moves the mosquitoes more gently into the surrounding air, making the release more continuous. Also, the white background on the inclined surface (and a camera pointing at it) allows the user to see and monitor the release using a real-time video stream.

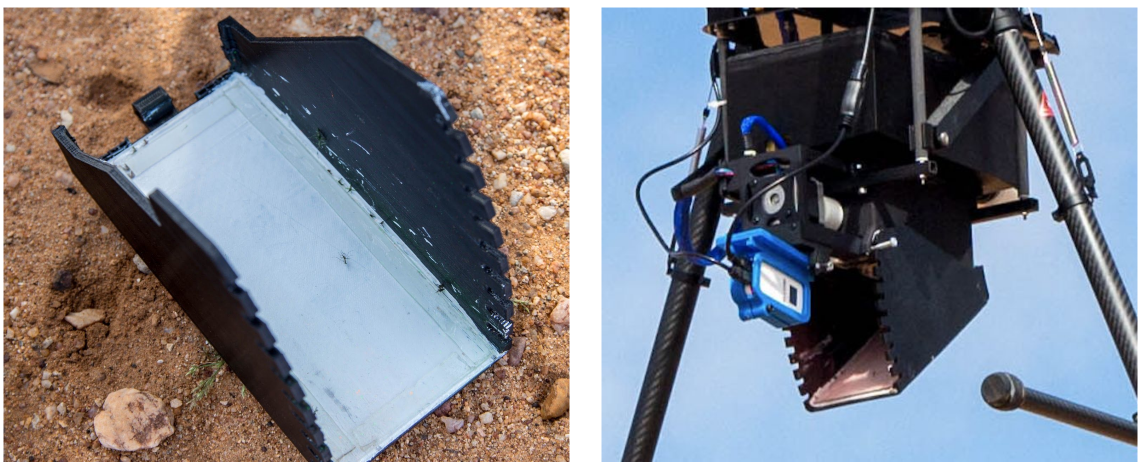


Figure: The release area ramp separately (left), and mounted on the release mechanism (right)

4) Onboard electronics: our onboard control is running on a Raspberry Pi 3 (RPi, low-cost mini computer), interfacing the drone (and ground station) with the release mechanism. A LCD screen is mounted on the drone and gives visual feedback of the onboard control when in the field. The stepper motor is controlled using an STM32 microcontroller and a motor controller shield that receives motor commands from the RPi.

In order to monitor the mechanism during flight, we embedded several sensors into the mechanism. Four temperature sensors are mounted at locations outside the mechanism, at the cylinder, at the canister wall and inside the canister. Two humidity sensors measure outside humidity and humidity in the canister.

Further, we mounted two cameras to monitor and live-stream the release area as well as the canister load and drone flight. The cameras give direct visual feedback to the user about the release of the mosquitoes.

Drone integration: the whole mechanism is embedded on a DJI M600 Pro hexacopter drone using a custom made holding structure that allows for simple mounting and unmounting.

Figure: The fully-assembled aerial mosquito release mechanism attached to a DJI M600 drone

3.2 Software

In order to run mosquito release missions autonomously, we developed a custom Android-based app that allows for efficient planning and running of such missions.

The main features of this ground station app is planning of flight route, speed and altitude, setting release points and rates, uploading a mission to drone, running a mission autonomously, monitoring drone state, mechanism state, sensor values and camera live-stream. Missions can be saved and loaded for repeating the exact same missions. In addition, KML files featuring GPS positions can be imported, allowing to plan the flight route using standard GIS tools.

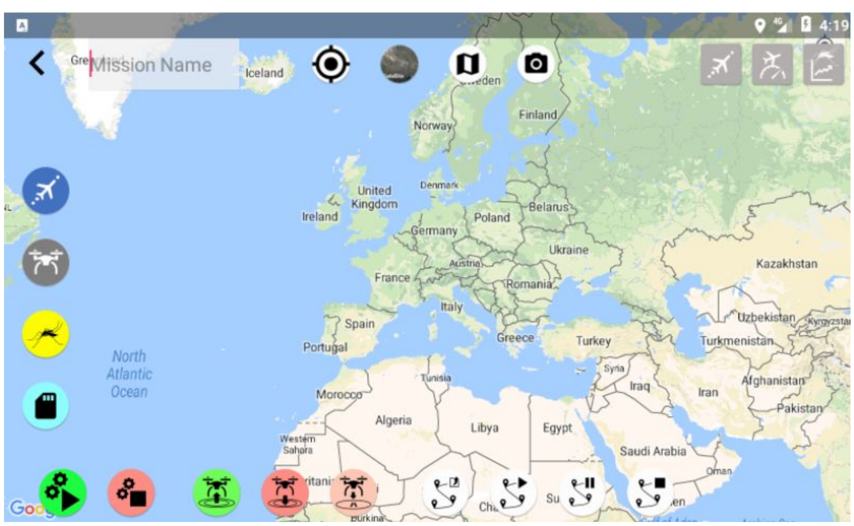


Figure: screenshot of the MosquitoApp

3.3 Testing and validation

In order to determine the cumulative effects of each stage of the aerial release (from immobilising, compaction and releasing from the mechanism) on overall mosquito quality, we conducted a competitiveness study in large 60 cm^2 cages using sterile adult males and compared it to a ground release (where all stages were the same as an aerial release but these adults did not pass via the release mechanism). We thus then calculated the competitiveness index and compared the two methods. The competitiveness index (*C*) was calculated as:

$$C = \frac{Hn - Ho}{Ho - Hs} * \frac{N}{S}$$

where H_n and H_s were respectively the hatch rate from eggs of females mated with fertile or sterile males, H_o was the observed egg hatch rate in the experiment (aerial release or ground release) and *N* and *S* were the numbers of untreated (100) and sterile males (300) respectively. Mean values have been calculated, with standard error and can be seen in the table below.

	Aerial Release	**Ground Release**
N Replicates	3	3
N Adults Released	300:100:100	300:100:100
Mean Eggs Produced	231 ±196	399 ± 155
Mean Hatch Rate	29.1 ± 1	29.1 ± 1.2
Mean CI	**0.66 ± 0.04**	**0.67 ± 0.04**

What our results from this experiment show, is that sterile males who were released by ground and by air are equally competitive or in other words, the release mechanism is not impacting the competitiveness of the sterile males. This result was reassuring as it showed that we have optimised conditions for storage and transportation, in addition to the design of the actual mechanism itself, successfully.

3.4 Calibration

In order to calibrate our system for a target mission, we mainly need to set a flight route, the release rate of the mechanism as well as the flight altitude.

The flight route is best set as a regular polygon pattern above the target area. The sidelap between each leg of the flight is mainly related by the dispersion of the mosquitoes. Assuming a dispersion of around 50 m, we choose the sidelap between the flight legs to be 80 m.

The release rate per area depends on the turning speed of the cylinder and the flight speed. Using the formula below we can derive a cylinder speed and flight speed for a target release rate for a given flight route/leg:

$$Release\ rate\ per\ flight\ line\ (Mosquito/m) = 5,000 * \frac{Cylinder\ speed\ (RPM)}{Flight\ speed\ (m/s)}$$

Finally, the flight altitude is dependent on the storage temperatures of the mosquitoes (and the following wake up times), as well as the mosquito drop speed. Given the drop speed of Aedes Aegypti of 2.5 m/s and wake up times of around 50 sec, we set the flight altitude to 100m. This should give the mosquitoes enough time to wake up after being released out of the mechanism before they would land on ground.

4 Mechanism field tests

4.1 Mortality test on the ground

A first test was performed to test the total mortality of mosquitoes that run through the full release process (immobilisation, compaction and release) in real environmental conditions. A net was built around the mechanism in order to capture all mosquitoes immediately after release. A full release scenario was then performed:

1. Mosquitos were cooled, then left for several hours in a cold-room, then packed into canisters.
2. Canisters were transferred to a portable cooler and left there for one hour, simulating transport to a field release site.
3. Canisters were loaded into the mechanism mounted on the drone.
4. A flight was simulated as close as possible to real conditions: a large fan was creating airflow over the mechanism similar to the flight speed of the drone, and the drone was run through a simulation program that started and stopped the release process as would occur during normal release.

Once the mosquitoes were released from the mechanism and caught in the net, the net was transferred to the cold room to immobilise the mosquitoes and then transfer them to a tray. The tray was placed in a large net, covered but with a small opening to allow mosquitoes to fly out and escape. After a day in the net, the mosquitoes remaining in the tray were considered dead or unfit to fly out, and were counted. The experiment was performed twice, with similar results detailed in the table below.

	Trial 1	**Trial 2**
Number released	49,400	49,600
Number remaining in tray after 1 day (counted - preliminary)	2,500	3,500
Number remaining in canister or mechanism (estimated)	1,000	1,000
Number escaped from tray (estimated)	46,500	45,500
Percentage flight-capable mosquitoes released	**93%**	**91%**

Figure: A net is built around the outlet of the mechanism (left). A flight is then simulated with airflow created by a big fan (right), and all mosquitoes are recaptured.

4.2 Mark-Release-Recapture field trials

A series of Mark-Release-Recapture (MRR) tests were organized to gauge the efficacy of the mechanism in real-world conditions and to estimate dispersion and homogeneity of the release. Tests were performed together with the generous support of Moscamed, based in Juazeiro, Brazil, in March 2018.

Staff at Moscamed Brazil are well-trained in mass rearing of insects and have been running pest-control projects and studies with fruit flies and mosquitoes for nearly a decade. The facility has a fully-functioning mass-rearing lab, an irradiation facility for sterilization of insects, a cold-room for packaging and tools, labs and staff for capturing and identifying insects.

Figure: The mass-rearing process at Moscamed Brazil. Clockwise, from top left: Storage centre containing food and consumables; pupae in trays; separation of pupae into males and females; irradiation of pupae; cages with adult mosquitoes; cold room for immobilisation and packing.

4.3 MRR site and test description

The MRR trials were organized in the town of Carnaiba do Sertao, several kilometers south of Moscamed's rearing facilities.

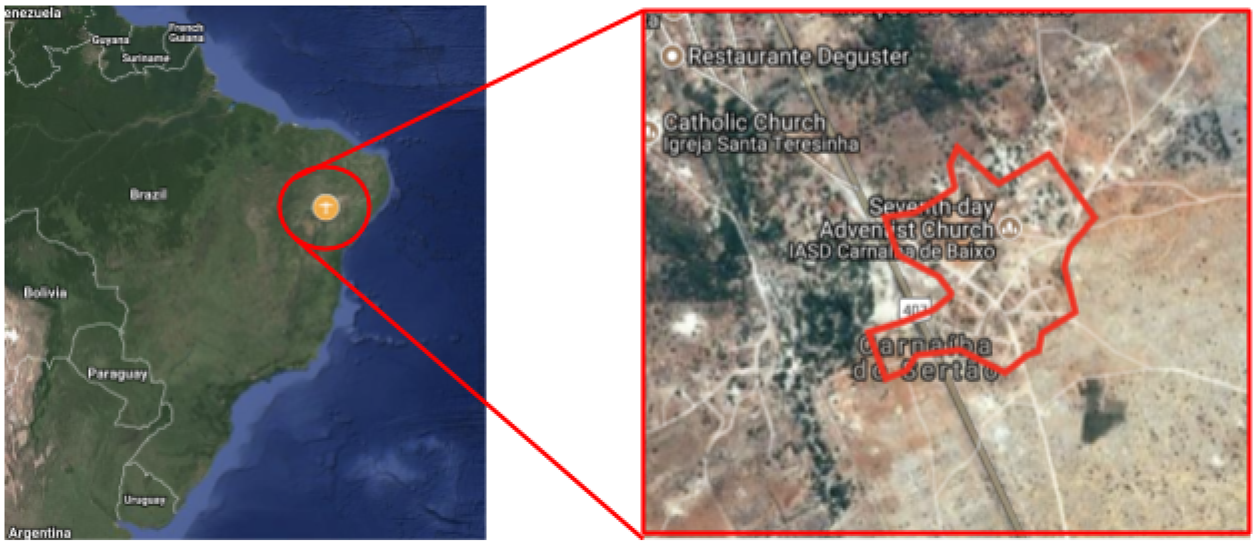


Figure: The town of Carnaiba do Sertao, in the state of Bahia, Brazil

For several weeks before the start of the trials the staff at Moscamed organized a community engagement campaign to explain SIT, gain local trust and buy-in to the project, and identifying houses that were willing to host mosquito traps during the length of the experiment. The campaign included flyers, radio announcements and house-to-house visits to the entire community.

The town covers an area of around 20 hectares. BG Sentinel mosquito traps were set up in 37 different locations throughout this area in order to measure both the baseline level of mosquitoes in the community as well as the sterile mosquitoes released during these tests.

Figure: Clockwise, from top-left: All traps were brought to the field, teams were split between different sectors of Carnaiba, traps were built in the homes of the community, subsequent daily trips to the community used to gather mosquitoes from the traps.

In order to distinguish the mosquitoes released during the test from the native population a fluorescent marking technique was used on the sterile mosquitoes. Several different colours of die were used in order to further distinguish mosquitoes from various releases. The color of the die, and thus the release that each trapped mosquito is associated with, can be seen under a UV microscope.

Figure: Clockwise, from top-left: Mosquito dies of different colours, plastic bins with pre-dusted mosquitoes, a canister full of pink-dusted mosquitoes, a mosquito that is visibly blue after release

4.4 Mosquito dispersion tests

A limitation of ground release is that mosquitoes do not typically travel more than 50m in a lifetime; it is hoped that releasing mosquitoes from the air can better disperse them over a wider area. In order to test dispersion, a first series of releases were performed to test the distance travelled by mosquitoes when released from a given altitude, and compared to a ground release.

A series of releases were performed around the centre of the football field of Carnaiba. Canisters with around 10,000 mosquitoes were release at altitudes of 50m and 100m, with a ground release at the same point used as a control. The same series of release was performed on two separate days - March 21 and March 24th, 2018. The figure below shows the release location, together with the locations of traps in the vicinity of the release.

Figure: Centroid of dispersion release (green), location of traps (blue houses) and circles representing 50m (yellow), 100m (blue) and 150m (red) from the release point centroid

4.5 Release homogeneity tests

Another presumed advantage of aerial release, compared to ground release, is increased homogeneity of mosquitoes over a given area, as a drone is not limited to following existing roads. In order to test this, the drone was flown along a regular programmed flight path consisting of straight, equidistant lines that covered a 20 hectare area above Carnaiba. The release mechanism was set to rotate at 2 RPM and the drone flew at a speed of 5 m/s, equivalent to a release of approximately 5,000 mosquitoes per hectare. The flights were performed at a fixed altitude of 100 m.

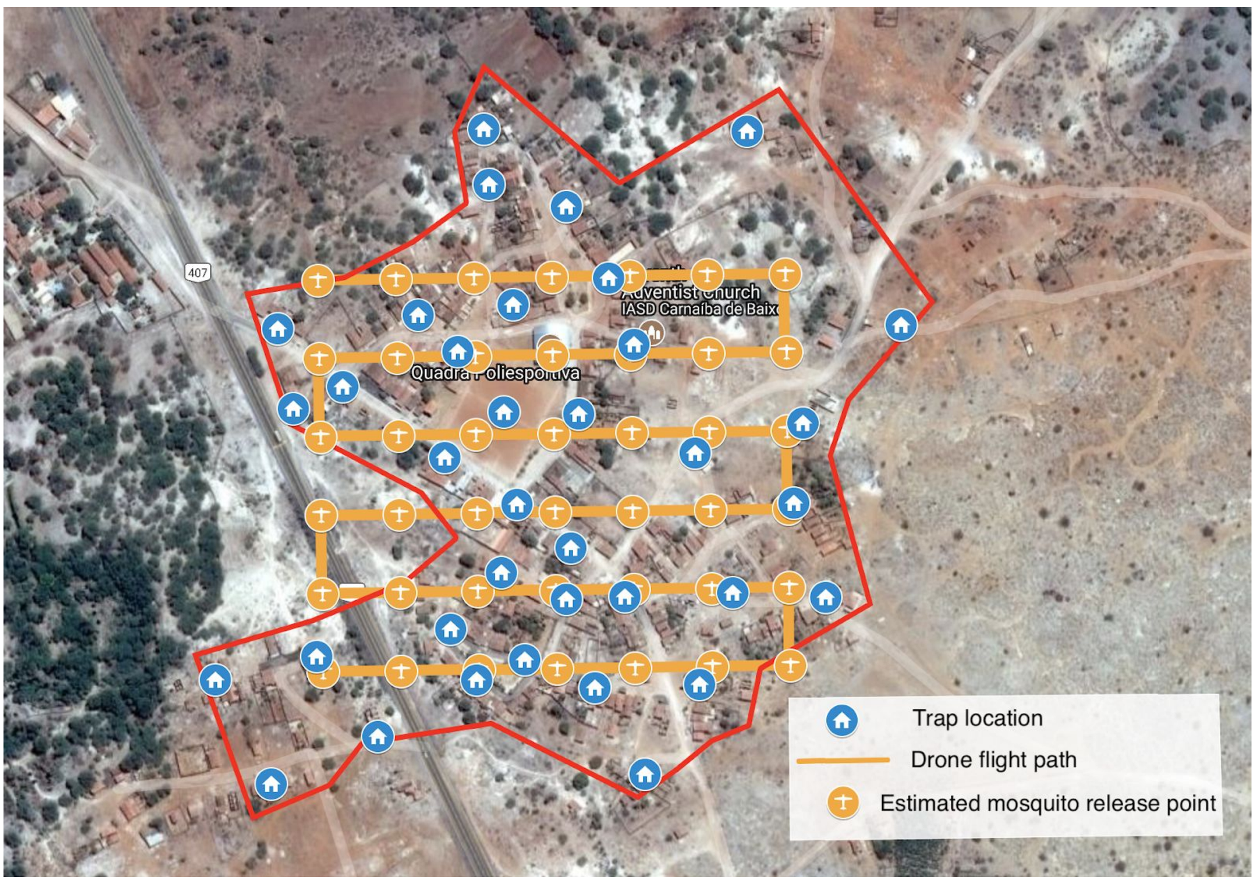


Figure: Flight path of the drone with estimated release points during the homogeneity tests, overlaid on trap locations.

Several flights were performed over 3 days. On the first release day (March 21, 2018), two flights carrying 50,000 mosquitoes each were performed - the first flew the southernmost three lines of the flight path, the second flew the northernmost three lines.

On the second release day (March 24, 2018), the same homogeneity flights were performed as on the first day. Unfortunately, due to excessive humidity within the canisters (due to high ambient humidity upon 95%), the mosquitoes started clumping together within the canister and not passing through the release mechanism correctly. The drone returned to the ground with mosquitoes still present in the canister, unable to be released. The entire experiment had to be discounted.

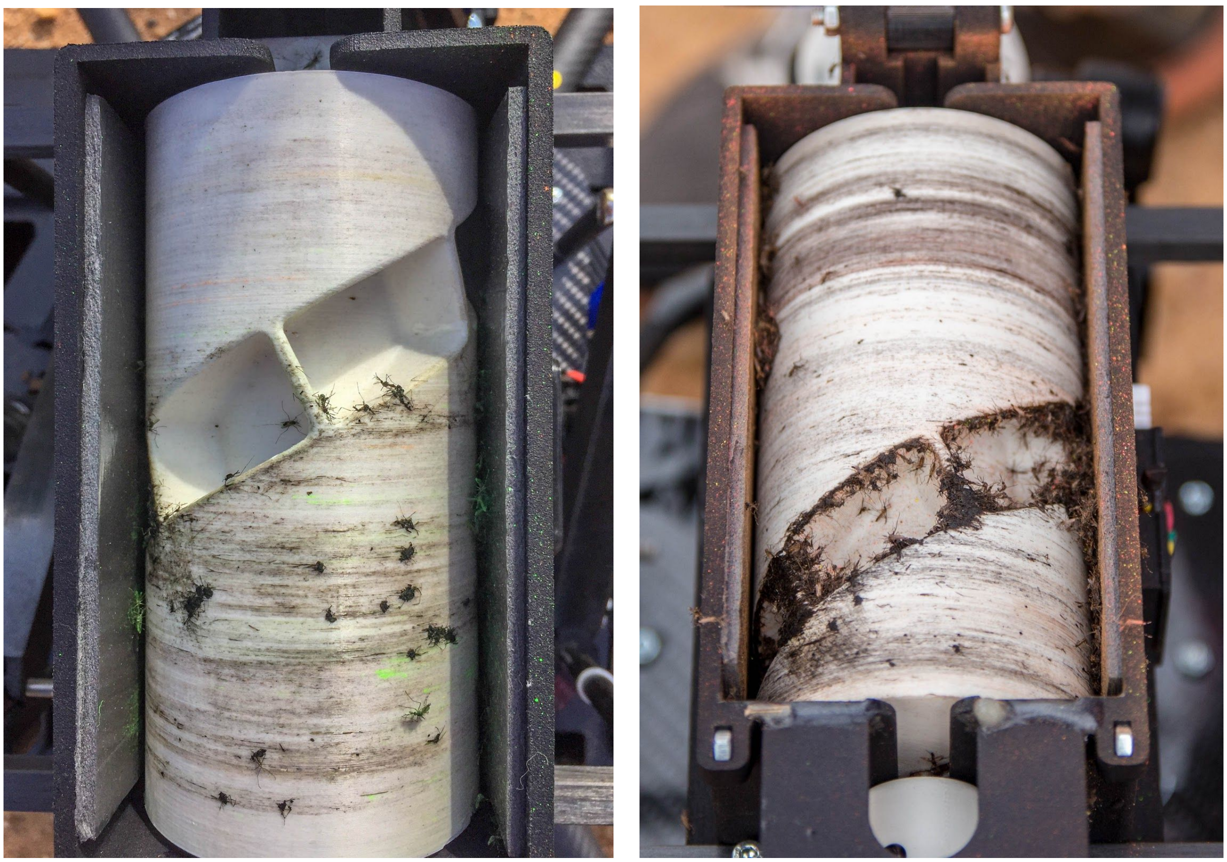


Figure: Left: a relatively clean cylinder with few crushed mosquitoes after a release in less humid conditions. Right: a cylinder showing many clumped and crushed mosquitoes, performed in more humid conditions.

A third release day was organised on March 27, 2018, with two canisters of around 35,000 mosquitoes each. More care was taken to control temperature and humidity along the entire cooling/packing/transport/release chain. To ensure that all mosquitoes were released, the drone flew the entire flight path above the village - the first flight starting from the South, the second starting from the North. This release was more successful, with all mosquitoes released from the canister.

4.6 Detailed field release schedule

The following table gives a summary of the various releases that were performed during the MRR trials.

Test description	Number of mosquitos	Marking colour
Release Day 1 - March 21, 2018 Temperature: 26 deg C, Humidity: 70% rel. H., Average wind: 5-10 km/h		
Dispersion - Ground (control)	9,600	Blue
Dispersion - 50m	9,600	Orange
Dispersion - 100m	9,600	Green
Homogeneity - South of town	50,700	Pink
Homogeneity - North of town	47,000	Pink
Release Day 2 - March 24, 2018 Temperature: 25 deg C, Humidity: 90% rel. H., Average wind: 5-10 km/h		
Dispersion - Ground (control)	9,600	Blue+Yellow
Dispersion - 100m	9,600	Green+Yellow
Dispersion - 50m	7,200	Orange+Yellow
Homogeneity - Entire town	49,000	Pink+Yellow
Release Day 3 - March 27, 2018 Temperature: 23 deg C, Humidity: 90% rel. H., Average wind: 5-10 km/h		
Homogeneity - South of town	33,600	Yellow
Homogeneity - North of town	32,100	Yellow
Total number of mosquitoes released	**284,200**	

5 Preliminary results and discussion

5.1 Mosquito capture data

Mosquitoes that have been trapped in each of the 37 traps are being collected every day since the start of the first release experiment. Each trap has a number, location and a distance from the central release point for the dispersion tests.

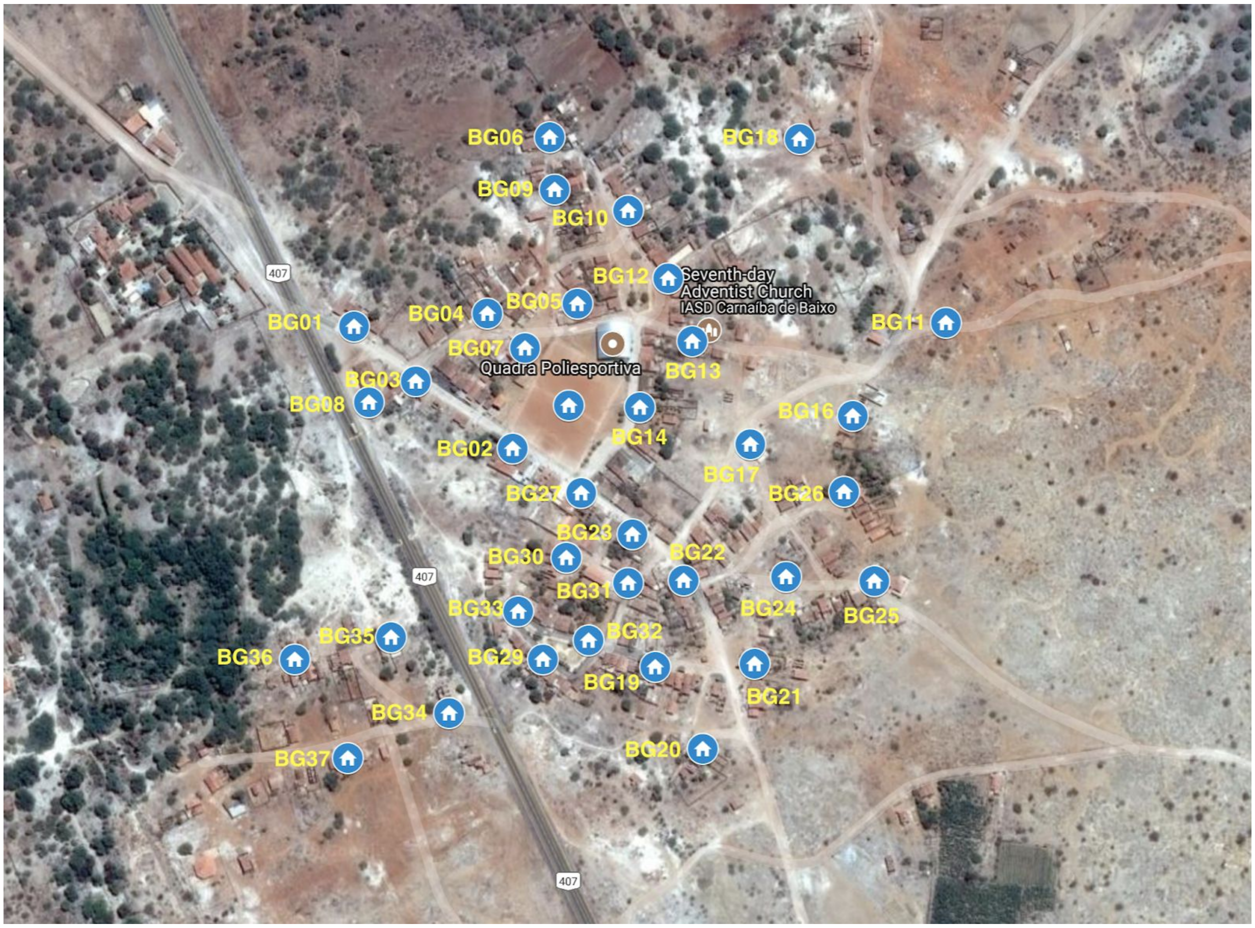


Figure: Trap names and locations in Carnaiba

The captured mosquitoes are then separated into species, with only the *Aedes aegypti* being preserved and counted. Preliminary results can be seen in the graphs below:

Figure: Preliminary number of captured mosquitoes in BG traps after release

While these are only preliminary results without precise identification of the marked colors, we estimate that roughly 60% of trapped male mosquitoes were marked and thus coming from either ground or aerial release.

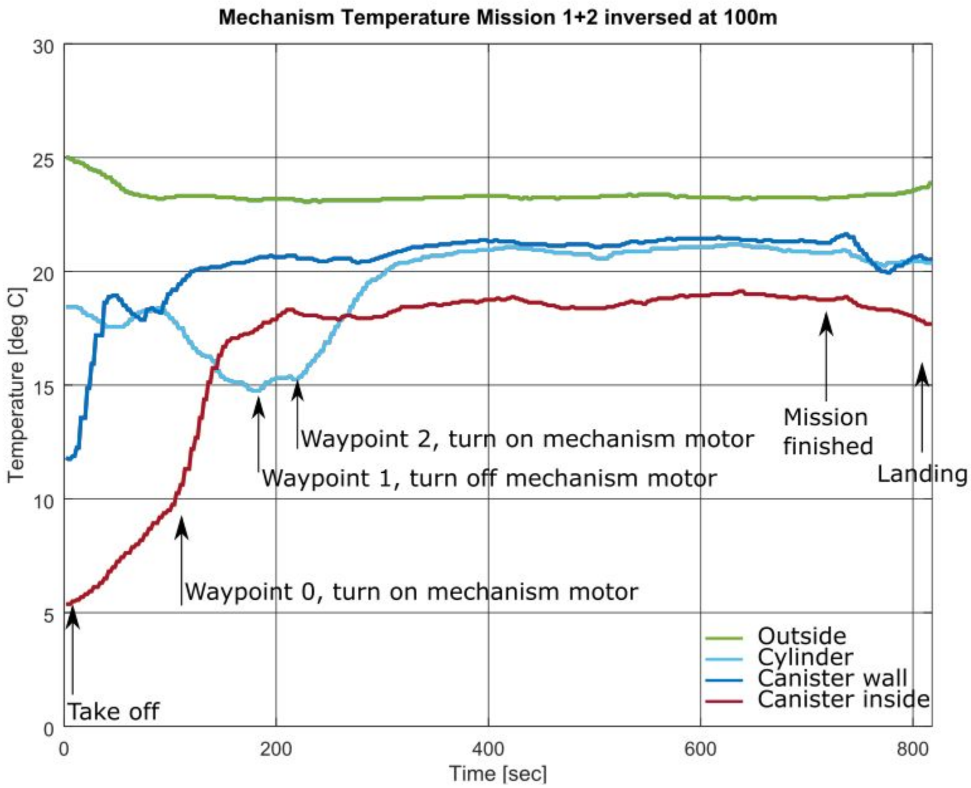
As we noticed during collection of the traps, some of the traps were rather misplaced (not in humid environment, not around vegetation, not in the shadows), hence leading to low collection numbers. Some of the traps were even malfunctioning due to missing electricity. In order to relate trap locations, flight route and colors of marked mosquitoes, further collection and analysis will need to be done.

Mosquitoes will continue being trapped until April 2, 2018, 1 week after the final release. The mosquitoes will then be transported to IAEA labs in Vienna, Austria, where the precise fluorescent colour will be identified using special microscopes and UV lamps. Final results expected in April 2018.

5.2 Initial observations

Though final results of the dispersion and homogeneity experiments are not yet complete, a few initial observations can be made that will guide further design modifications of the release mechanism and its use in more important release campaigns:

- Detailed lab tests on the resistance of mosquitoes to environmental and mechanical stresses are a key component of the design process and should be performed as early as possible. Immobilizing, transporting and releasing chilled adult mosquitoes presents many new challenges that are not dealt with through traditional ground-based release. In particular, mechanical stresses on the mosquitoes as they pass through a mechanism designed to separate them into smaller batches can very easily damage their wings, making them essentially useless as potential mates after release. In additional, compacted mosquitoes behave like no other fluid or material - their legs lock together and they form groups of interlocked insects that create “clumps” that are not easily separated. Early and regular tests of mechanical components of the mechanism using live mosquitoes is thus key to a successful design.
- Detailed sensor data and instrumentation is important, especially during aerial release with live mosquitoes. Measuring temperature and humidity provides valuable input to the design of cooling systems, airflow control and transportation protocols. Camera views during flight give valuable insight on the actual release behaviour while the mechanism is airborne.
- Temperature and humidity control within the canister containing the compacted mosquitoes is critical to release success, and remains a significant challenge. As shown in laboratory tests, mosquitoes must absolutely remain below 10 C in order to avoid damage. As soon as the mechanism begins spinning, however, hot air from the outside mixes with the air in the canister, quickly increasing internal temperature. Not only does the temperature rise, but the clash of hot, humid air on cold mosquitoes creates condensation, which exacerbates the problem of clumping. Such an effect cause the failure of release during the second day of testing.



Better control of temperatures is thus critical in any future mechanism design. The current design is split into cold (canister) and hot (mechanism) sections; perhaps splitting the design into three sections, adding a mixing area between the canister and the mechanism, can decrease the risk of clumping of mosquitoes during longer flights.

- Precise control of release rate is still a challenge. As the canister is emptied the release rate tends to decrease, as some of the holes in the cylinder are no longer fully filled with mosquitoes. Flow rate is currently observed in open-loop using the on-board camera, and no existing sensor has yet been developed to measure this flow rate. Perhaps the addition of computer vision algorithms or some other novel sensing techniques can be implemented to close the sensing-actuation loop and increase homogeneity.
- The machine itself is still rather bulky. Some improvements in robustness could be included. We can also increase mosquito capacity for a single flight. In this series of tests we emptied a full canister of 50,000 mosquitoes in less than 10 minutes. The flight time of the drone can reach 20-25min, the drone can fly significantly faster than it did during current tests, and the mechanism can be turned at higher speeds. There is thus a strong chance that the area covered by a single flight can be significantly increased beyond 20 hectares.

6 Conclusion

Over the last 12 months we have developed and validated a robust, easy-to-use, drone-based aerial release mechanism for mosquitoes. The mechanism is capable of releasing 50,000 mosquitoes in a single flight, and it's removable-canister design enables multiple flights and release over areas of over 100 hectares in a single morning. Through a series of lab, ground and aerial trials we have demonstrated a low mortality rate of less than 10% and competitiveness similar to ground-released mosquitoes. Further analysis of our MRR trials will quantify the mechanism's capacity to homogeneously disperse mosquitoes over a wide area.

This design prototype demonstrates drone-based aerial release as a viable technology for releasing mosquitoes used for disease vector control. The lessons learned in this project will allow further development and refinement of the mechanism, making it more practical, affordable and accessible for the control of *Aedes aegypti* populations.

Drone-based aerial release is, however, just one component of a successful vector control strategy, and should be combined with ground-based release when appropriate and economically viable. It's biggest advantage is being able to reach difficult areas inaccessible by road or for reducing release costs in large-area campaigns.

Going forward, we hope to industrialise this technology and make it available as a package to existing and future vector control campaigns. As part of WeRobotics' mission of localization of robotics technology, we will package the technology with training of local drone operators and support of local aviation authorities in order to make the technology locally owned and safe to operate.

As treatment areas and release campaigns scale and multiply around the world, the role of our aerial release technology will become more integrated in large-scale campaigns. It is the hope of the authors that this technology will contribute to the efficient control of debilitating and deadly diseases such as Zika, and ultimately, the improvement of lives of affected communities throughout the world.

7 Acknowledgements

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Figure: The WeRobotics, IPCL, Moscamed, and regional partners that all took part in our aerial mosquito release trials

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