# Robotic Pollination - Targeting Kiwifruit Flowers for Commercial Application

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**This paper contains the initial evaluation of a novel platform mounted robotic pollination system. Advancement in artificial pollination is an important step forward in agricultural sectors due to the global decline of natural pollinators. Robotic pollination allows for potentially autonomous, precision operation; however, background research suggested that prior development in the area has been sparse. The featured wet-application robotic pollination system was capable of detecting >70% of flowers whilst driving at a slow-pace through kiwifruit orchard rows. Over 80% of flowers were robotically pollinated.**

Key words – Pollination; Robotics; Detection; Kiwifruit; Horticulture

## 1 Background

### 1.1 Reform in fruit pollination

In prior years, natural pollinators have provided adept agricultural pollination for global crops. However, there is mounting evidence of pollinator decline all over the world and consequences in many agricultural areas could be significant [8]. During 2010, it was proposed that a global mean 87.5% [12] of flowering plants depended on biotic pollination to sexually reproduce. As a tangible measure; biotic pollination by insects is deemed to be worth €50.6 billion [8] to global fruit growers, corresponding to 23.1% of the total production economic value of fruit. The honeybee, a well-studied and primary insect pollinator, is estimated to be capable of increasing yield by 96% in naturally pollinated crops [15]. Thus, honeybees are commonly used to intensify fruit production on horticultural plots in the form of naturally occurring bee colonies or managed colonies in adequately placed hives. Whilst there has been a global honeybee colony increase of 45% from 1961 to 2006, animal-pollination dependent crops have increased by greater than 300% [2] in the same time period. Essentially, global bee stocks are growing slower than their agricultural demand. In addition to this, many areas are currently experiencing honeybee colony decline. This decline is due to a number of reasons ranging from habitat degradation, invasive species, increased pathologies, pollution, insecticides and as of 2006 colony collapse disorder (CCD); a phenomenon whereby the colonies inexplicably lose their workers [5]. CCD has been estimated to cause a loss of 50-90% of managed bee colonies in the United States. An unlikely, but certainly possible scenario in later years given rates of decline, is that natural pollinators such as honeybees diminish to the point of providing no pollination contribution whatsoever. Whilst the ecological impact from such a scenario is likely to be large, the immediate economic impact to the fruit industry has been projected as a 12% reduction in fruit production [8].

To speculate qualitatively on the preceding figures, the increasing decline of natural pollinators will have negative economic, humanitarian and ecological implications. Lack of natural pollination will likely impact in the fruit industry, which is particularly sensitive due to the lack of abiotic crop pollination. Continual growth of pollinator reliant fruit crops may well be a long-term financial risk, however this seems to be a growing trend [26]. An already used and actively invested solution is artificial pollination. Artificial pollination relies on pollen harvesting and non-natural pollen distribution onto female reproductive organs of the plant. When considering that horticultural economic welfare may potentially hinge on the prosperity of sensitive terrestrial ecosystems, artificial pollination becomes a necessary avenue of advancement and may well become an intrinsic element of all future crops.

## 1.2 Advances in artificial pollinators

### 1.2.1 Mechanized and basic machines

Kiwifruit are New Zealand’s largest horticultural export, worth over US$1.3 billion in annual revenue [29], and are particularly sensitive to the presence of bees in order to pollinate. In 1982, S. Martin assessed the number of beehives available to kiwifruit pollination and concluded that there could have been a 60000-beehive shortfall by 1990 [11]. Her work, along with that of M. Hopping [22], inspired extended development in artificial pollinators. Hopping proposed a number of prospective artificial methods for comparison (1982) [10]:

- Manual hand pollination (by brushing male flower over female flower)
- Flower dips (by dipping flower in a pollen suspended fluid)
- Puffer gun (using pollen diluted with talc)
- Hand operated pressure sprayer (using Cambrian sprayer with pollen suspended fluid)
- Boom sprayer and pressure vessel (spraying pollen suspended fluid at 3 km/h on back of tractor)

The mechanized methods of hand operated pressure sprayer and boom sprayer did not impair pollen viability despite the use of an aqueous suspension media. The major limitation with these methods was deemed to be the insufficient capture of pollen grains on stigmatic surfaces [10]. However, more recent experiments from Japan in 2007 [27] with revised pollen concentration and suspension media, suggest that spray pollination is superior to that of hand pollination (manually brushing flowers with feather stick brush) in kiwifruit. It was also found that the time taken to spray flowers manually was more than twice as fast as brushing by hand. These observations were echoed in the spray pollination of Japanese pears [17], where spray pollination was not only twice as fast to perform manually compared to brushing by hand but also required a third of the pollen.

Other documented early adopters of mechanized artificial pollination included mechanical dusting of apple orchards [25] and the mechanical blowing of date palm trees [14]. The date palm mechanization project began in 1961 and was introduced to mitigate the decreasing labor force of experienced tree-men (700 men were required for manual hand pollination and 900 men were required for harvesting dates across the Coachella Valley, US). Six pollination machines were built and used during the 1973-1974 season to positive effect; reducing overall labor requirement between 50-70% and able to equal or exceed hand pollination efficacy [14]. The machine itself consisted of a platform and delivery tube attached to a forklift mast for 15ft of vertical adjustment, this also doubled as a successful pesticide distributor when not in pollination season.

In recent years, many other pollen blowers, dusters and spray dispensers have been introduced to keep modern crop production competitive. Companies such as PollenPlus™ in New Zealand provide pollination services to kiwifruit orchards [30]. They use mechanical blowers, Cambrian sprayers and their ‘QuadDuster’ – a quad bike with attachments for mechanical pollen

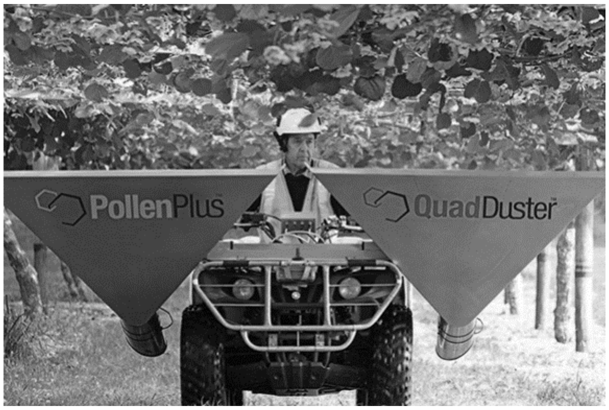

*Figure 1 - PollenPlus™ QuadDuster* [30]

dusting [Fig 1]. Other notable mentions in mechanized artificial pollination:

- Battery powered portable duster used by Razeto et al (2005) [16]
- TurboBee, Variflo, Airflo, Airshear, Dry-pol and Hanakaze [9]. All are artificial pollinators used in the Kiwifruit industry

In summary, evidence was found for use the of mechanized and basic machine pollination dating back to the 1960's, however the origins of the practice likely date back much further given the scope of agriculture. Whilst mechanized sprays and dusters demonstrate significant labor savings over manual hand pollination, they still require a human element in their operation as well as the harvest of pollen; an expensive procedure in itself (New Zealand kiwifruit pollen costing US$2500 per kg in 2016 [13]). As an increasing percentage of the horticultural industry becomes reliant upon artificial pollination, a growing demand will be placed upon researchers, scientists and engineers to develop cheaper and more efficient pollinator options.

### 1.2.2 Robotic and complex machines

This section will consider mechatronic (computer controlled, electromechanical) artificial pollination systems. These systems are advantageous over basic mechanized systems in that robotic machines can utilize sensory information to make 'intelligent', calculated decisions in their environment such as flower detection and autonomous operation. Despite being arguably the most difficult subset of robotics [23], mobile field robots have already arrived at a stage where they can start to provide economic benefit in several areas of their operation. However, robotic pollination seems to be still in its infancy.

Exploring preexisting literature in robotic pollination suggests two fundamentally different approaches to the task. The first approach is the use of a platform with manipulator and some sort of spraying head, the second approach is for the robot to fly in the form of a drone or robotic bee imitation. The recent miniaturization of sensory, computational and actuation machine elements has allowed for novel micro aerial (MAV) and nano aerial (NAV) vehicle designs. Berman et al from Harvard University have proposed methods in control policies and coverage strategies for aerial vehicle robotic swarms with an application in pollination [3][4][7]. Abutalipov et al (2016) have also proposed nano-copters (drones) as robotic pollinators [1]. However, despite rigorous modelling of the aerial vehicle approach to pollination, nothing currently exists as a practical design or as an actual, physical system to validate. Robotic bees *are* currently under development, notably by Robert Wood and his team at Harvard University, but they require tethered power and control so are still a long way off being viable pollinators [24]. Macroscopic platform based robots on the other hand, have been designed and trialed before; there are four documented systems of note. An autonomous, greenhouse based, tomato-pollinating robot using stereo vision was able to detect single flowers 50% of the time and took, on average, 15 seconds to pollinate a cluster of flowers [28]. It was comprised of a track-driven autonomous platform and 4DOF robotic arm with solenoid operated spray nozzle. A robotic docking crane system was used to simulate the pollination of vanilla flowers. A main gantry crane is used to hoist and dock a slewing unit structure that supports a balanced pair of vision feedback cranes. Each vision feedback crane is supported by six winches to provide six degrees of freedom [20] for camera dexterity. A visually guided date palm tree sprayer has been developed in Israel that uses a 2DOF spraying head on a winch-operated telescopic mast that sits on a towed platform [21]. The mast is also radially actuated by an electric cylinder so that the spraying head ultimately has 4DOF's relative to the platform. They concluded that at platform velocities up to 1.25 $ms^{-1}$ the angular spraying error is less than 10 degrees, which is less than the solid angle of their spraying jet and thus feasible for future scaling. In 2012, Plant and Food research in New Zealand proposed the use of a platform based spray manifold that could be towed/driven around orchards for kiwifruit pollination [32]. This machine, unlike manifold type designs before it, used a sensory array to confirm the presence of a flower before initializing the spray nozzle to hit it. By doing this, they could be much more efficient with pollen than prior developed purely mechanical methods.

## 1.3 Experimental aims

The aim of this paper is to introduce a novel platform mounted robotic pollination system. The system will need to operate in kiwifruit orchards for kiwifruit flower pollination and will aim to be competitive with preexisting commercial methods. The design of the system will factor considerations and limitations from the aforementioned robotic pollination systems. The team behind the project is the CoHort (collaborative horticultural) robotics team in New Zealand.

# 2 Theory

## 2.1 Cost and efficiency specification

For commercial application, the robot will need to have a payback period of 2-3 years. To be cost competitive with other methods, the robot will need to pollinate a hectare of kiwifruit orchard with less than 800g of pollen. For a modern, high crop-load orchard, there can be in excess of 500,000 flowers per hectare. Literature on wet-application kiwifruit pollination suggests 12000 grains of pollen per flower is sufficient to yield 100g export-quality kiwifruit [6]. Thus, at approximately 6ng per kiwifruit pollen grain, 72µg of pollen would have to be distributed onto flower stigma per spray. Over a hectare, this corresponds to 36g of pollen, meaning the system would need to be >4.5% efficient at distributing pollen onto flower stigma.

Estimates for capital cost of robotic hardware, comprised of a full pollination subsystem and half the capital cost of an autonomous platform (platform can also be used for harvesting kiwifruit), sit around US$90000. For a 2-year payback period, a US$45000 net-profit would need to be made over the course of each annual ≈30-day pollination season. Resulting in a required average net profit of US$1500 a day. A 30% profit margin on cost equates to approximately US$750; meaning the robot would need to be capable of pollinating two hectares per daily 7 hour pollination window (germination does not occur at below 12-14°). In a worst case scenario there might be two different site locations in which pollination needs to occur per day, resulting in *potentially* an additional 2 hours set up time. Thus, the robot will need to pollinate a hectare in under 2.5 hours. The machine would also need to pollinate a minimum of 90% of flowers; any less and lost revenue from crop yield would make the system impractical. With three stages of potential loss throughout the system (stereo capture, image processing and shot accuracy), each stage would need to have an average efficiency of 96.5% ($0.90^{1/3}$).

## 2.2 Physical Design

An individualist approach to flower targeting was investigated. The system would need to pollinate a flower in 18ms to achieve the commercially viable rate of an orchard hectare per 2.5 hours. For a robotic arm mounted spray nozzle, similar to that used by the aforementioned tomato pollination robot in section 1, realistic minimum time for pollinating per flower is 500ms (50ms image processing, 50ms spray actuation, 300ms arm manipulation to flower target and 100ms combined system delay). Thus, 28 robotic arms would be needed to be commercially viable; this is not a practical solution for a single platform system.

An aggregate approach was investigated in the form of a large, manifold array of electrically actuated spray nozzles. This approach has been proposed and prototyped by New Zealand Plant and Food research, collaborative partners in the CoHort robotics team. A typical kiwifruit orchard row is approximately 4-5m wide. A robotic platform could harbor a large spray nozzle array offering 4.5m of canopy coverage. At ≈10mm nozzle spacing the system would consist of ≈450 nozzles to account for positional variance of the flowers. To pollinate a hectare in 2.5 hours the platform would need an area coverage rate of 1.1m$^2$s$^{-1}$, therefore the platform velocity would need to be at least 0.24ms$^{-1}$ to be commercially viable at 4.5m canopy coverage. Kiwifruit flowers vary in distance from the ground by some degree in all kiwifruit orchards, this difference in height can range as much as 300mm. Failing to adjust for this height variance could significantly reduce commercial viability due to a plummet in pollen distribution efficiency. Therefore, at 100 mm flower-cluster spacing, the system would need to adjust a manifold height of 300 mm in 0.4s. To achieve this, an actuator would need to dynamically reposition the manifold at a peak acceleration of 7.5ms$^{-2}$. Factoring in gravity, the actuator would require a peak force of 1.73kN and peak power output of approximately 2.6kW per 100kg of manifold section.

To summarize, the system would require the following:

- Payback period of 2-3 years
- Distribute 72µg of pollen onto flower stigma
- >4.5% pollen distribution efficiency
- Pollination time of 2.5 hours per hectare (18ms per flower)
- An average efficiency of 96.5% for stereo vision capture, image detection and shot accuracy at minimum of 0.25 ms$^{-1}$ platform speed
- Platform mounted manifold spray nozzle array covering 4.5m of orchard canopy at ≈10mm nozzle spacing
- Dynamic actuation of manifolds capable of applying 1.73 kN and 2.6k W per 100 kg of manifold section.

# 3 Material and Methods

## 3.1 AMMP (Autonomous Multi-Purpose Mobile Platform)

The AMMP (Autonomous Multi-purpose Mobile Platform), is a modular autonomous robotic platform developed by the CoHort (collaborative horticultural) robotics team based in New Zealand. The premise behind the AMMP's design was to create an integrated system capable of autonomously navigating horticultural orchard rows whilst harboring robotic subsystems in order to carry out laborious tasks. The platform is essentially an evolution in technology motivated by the work of founding member and director of Robotics Plus, Dr. Alistair Scarfe. Scarfe originally proposed a prototype autonomous kiwifruit harvester for potential commercial application in accordance with his PhD at Massey University [19][18].

*Figure 2 – The AMMP during an initial test outing*

The goal for the 2016 kiwifruit pollination season was to evaluate a robotic pollination system that would act as a sub-system on the AMMP. The AMMP is a four-wheel drive series-hybrid, has variable speed control up to 10 km/h, can operate over a range of agricultural terrain and can perform 180º turns at the end of orchard rows by essentially pivoting about the center of its rear axle . These attributes, combined with the practicalities of full manual control, ease in transportation and an onboard compressed air supply have meant the AMMP has been instrumental in providing a platform for this experiment.

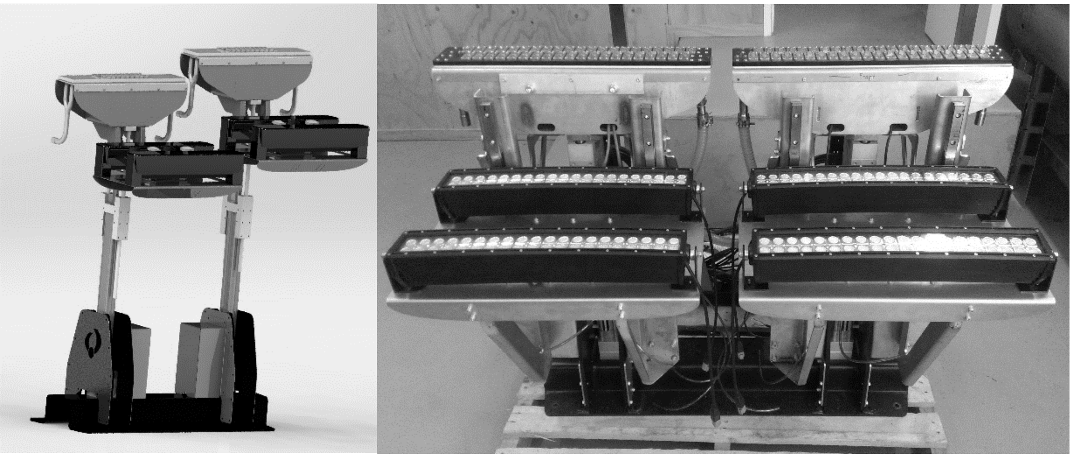

*Figure 3 - An early 3D CAD model of the pollination system (Left), Final manufactured dynamic spray manifolds with orchard canopy lighting as used in experiment (Right)*

## 3.2 Pollination System

Spray manifolds used on the experiment featured 40, solenoid operated, pollen delivery nozzles with a 12.5 mm spacing [Fig. 3]. Plant and Food Research, a collaborative partner on the CoHort team, produced the manifolds. Orchard canopy variance warranted spray manifolds that could dynamically height-adjust to maintain a suitable operating distance. The spray-nozzle array coverage over two manifolds is 1000mm in length on the featured system, as opposed to the proposed 4500 mm proposed for commercial viability. This is for prototyping purposes. Dynamic height adjustment was performed by servomotor driven, electric ball-screw cantilever actuator with 400 mm stroke.

Each spray manifold was equipped with its own vision system that included two 200 W radiused LED light bars to provide canopy illumination and two for stereo vision. This vision system was mated to the spray manifolds so that they could also dynamically height-adjust to maintain a suitable operating distance. At a software level, the pollination system was controlled via the ROS (robotic operating system) framework and image processing was achieved through a CNN (convolutional neural network) which proved effective in detecting kiwifruit flowers.

## 3.3 Spray observations

Cameras were mounted in several locations on and around the pollination system, so that spray characteristics and 'flower hit' accuracy could be visually recorded. For video analysis, several unobstructed orchard runs were slowed to 0.03x speed where parameters were measured such as: shots sprayed, flowers sprayed, flowers seen and relative velocities. An additional method shot-count method was audio analysis. The post-processed stereo vision footage was also recorded so that a correlation could be inferred from what the machine 'saw' and what was effectively sprayed.

## 3.4 Orchard experimentation

Experimentation involved the AMMP-mounted pollination system spraying unpollinated flowers down kiwifruit orchard rows during peak flower bloom (Nov 2016). Pollination spray efficacy was recorded at a range of platform velocities, over several orchard rows. Trials occurred at two separate orchards.

## 4 Results and discussion

During the day, from flower data set with 809 flowers, the machine stereo vision was able to capture 83.0% of the flowers. On a separate 903 flower data set, the neural network image processing detected 89.6% of kiwifruit flowers from the stereo vision capture. Combining these efficiencies, 74.37% of total flowers (including occluded flowers) were detected and able to be scheduled for spraying. This rate decreased to 69.98% in the dark, at night.

*Figure 5 - Machine vision detection of kiwifruit flowers in real-world orchard environment*

From a representative day-time orchard trial run at 0.36 m/s, an average count of 1045 shots were sprayed with an average count of 594 flowers having been hit; corresponding to a hit rate of 56.84%. However, with an average total flower count of 732 in the spraying window, 81.15% of total flowers were hit – 6.8% more than what was detected. This was due to over-spraying, where there were nearly double the number of shots sprayed than there were flowers (approximately an additional 92%); causing flowers to be hit that were not detected. A delivery nozzle 'on time' of 30 ms$^{-1}$ corresponded to a 730±50µL solution delivery at 2bar. At 8gL$^{-1}$ pollen concentration, a total of 5.84 mg of pollen was distributed per shot. Whilst the crop load (fruit density in canopy) will vary between orchards, an average estimate was made for 500,000 flowers per hectare; based on counts of between 40-60 fruit per m$^2$. The system, when considering over-spraying and flower detection inefficiencies, would then spray approximately 715,000 shots of pollen solution (4.18kg of pollen) per hectare for ≈ 81% flower coverage. As it currently stands, this system uses too much pollen to be competitive with other non-robotic, mechanized methods and does not meet previously calculated commercial specification. The Cambrian hand-operated sprayer is another wet-application device commonly used for artificial kiwifruit pollination and uses 760g of pollen per hectare [31], which is over 5 times more efficient with pollen than the proposed robotic system; a per hectare cost saving of US$8660. However, as an initial attempt at developing an integrated pollination robot, this system shows great promise in many areas of its operation. In particular, the image processing showed great merit and at ~ 90% flower recognition, based on the data recorded from other robotic pollinators featured in section 1; it may be the most advanced kiwifruit-flower detection system being used today. The system still requires some development and scaling of certain elements in order to reach commercially viable specification [section 2].

*Figure 4 - Pollination system mounted on AMMP during experimental orchard trials*

## 5 Conclusions and future work

Natural pollinators are of huge economic importance to the fruit industry but their populations are declining and unable to meet the numbers required for comprehensive pollination in intensive crop environments. Artificial pollination is seen as a method of addressing this.

Typically performed manually or by way of mechanical sprayer, artificial pollination is currently in use throughout the world. Robotic pollination is a progressive variation whereby autonomy and precision operation can aid in removing the human element from artificial pollination. In this paper, a robotic kiwifruit pollinating system was theorized with a design specification that would enable commercially viable operation. The physical robotic system featured and trialed was not able to meet these specifications, but showed great promise. Notable results were its ability to detect over 70% of flowers and hit over 80% of flowers at a platform speed of 0.36 $ms^{-1}$. Future work will include scaling the manifolds to full orchard row width of 4.5m and the optimization of machine vision, pollen distribution and shot accuracy such that the system can offer a commercially viable solution.

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