Automated Entrance Monitoring of Managed Bumble Bees

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Abstract. Social pollinators are a critical part of our ecosystem and a great source of inspiration for engineered swarms. Recently, researchers have produced a range of systems for automated monitoring of honey bee entrances to further insights on e.g. collective foraging, labor distribution, and suppression of disease transmission. In this article, we detail the design of a system customized for capturing top and side view photos of bumble bees as they enter and exit their hives. We show how these photos can be used to automatically track foraging activity, identify individuals, and characterize bee size and pollen presence. To aid technology adoption by biologists, our design is specifically optimized for low cost, easy fabrication, operation, and maintenance. Over two iterations, the entrance has been used on 6 hives in greenhouse and field over 7 weeks.

Keywords: Social insects, automated monitoring, field instruments

1 Introduction

Insect pollination is crucial for most crop production, but modern crops are often grown in conditions that are unfavorable for native wild pollinators. Consequently, many mass blooming crops require the addition of managed bees, which have increased greatly in price over the last three decades due to unsustainable losses stemming from pesticides, pathogens, and parasitic mites [1]. Better insights into the life cycle and foraging patterns of managed bees may further fundamental understanding of these biological swarms and inform pollinator friendly farm practices. Insights may also inspire new coordination algorithms for exploration with artificial swarms, similar to how pollinators collectively survey large geographical areas for brief spatio-temporal bloom events [2].

Over the last decade biologists and engineers have teamed up to produce a wealth of systems to help automatically monitor the activity of managed pollinators. As the premiere pollinator bringing in over 150 billion USD annually[3], the honey bee has gained the most attention. The majority has focused on attachments to bee boxes, with the ability to measure entrance activity of the hive through infrared break-beam [4,5] and camera sensors [6,7,8], often supplemented with wireless access and additional hive sensors such as thermal, humidity, and acoustics [9,10]. Several of these solutions require rather expensive and specialized infrastructure, such as high end cameras or IR tunnels, but more recent work has focused on accessible, low cost options based on embedded computers like the Raspberry Pi (RPi) [6,11]. The applications range from simple entrance counts to recognition of Varroa mites and pollen loads [12].

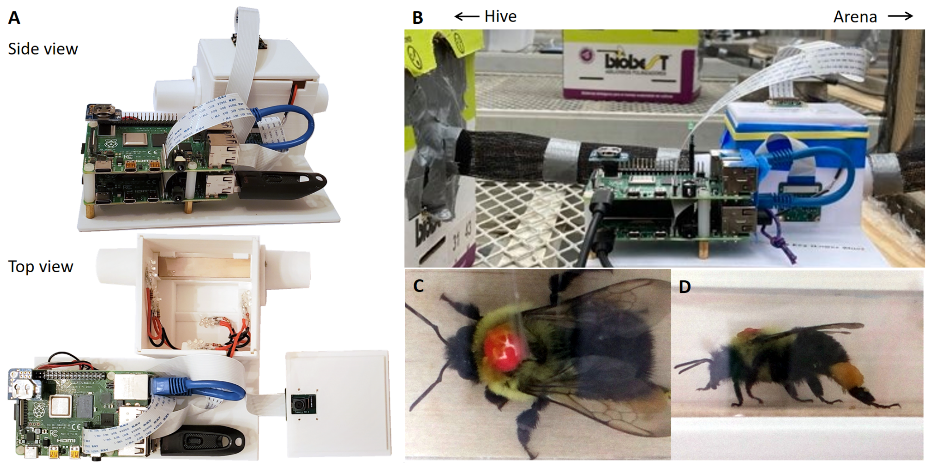


Fig. 1: Automated entrance monitor (A-B) capturing top and side photos (C-D) of bumble bees as they enter and exit their hive; the bee shown is carrying pollen. Note that to fit this article, all photos have been post-cropped.

In this article we focus on a low-cost entrance monitor for managed bumble bees that requires little know-how to operate and manufacture (Fig. 1). Although pollinator management often focuses on honey bees, managed bumble bees are important for agricultural pollination and especially popular for greenhouse applications. They are essential for pollinating crops that require buzz pollination, for which flowers must be vibrated at a high frequency in order to release pollen, such as tomato, blueberry, and cranberry. Additionally, bumble bees continue to forage when it is cold or raining, making them suited for pollinating crops that release their pollen early in the season or early in the morning when it is still too cold for honey bees to forage, such as apple and watermelon, respectively. Monitoring the entrance activity for bumble bees poses a different set of demands as compared to honey bees: 1) Commercial colonies are small, typically a few hundred workers; 2) Hives typically have a single or at most two entrances and exits that fit one bee at a time; 3) Bumble bees vary widely in size (10-30 mm, 40-320 mg) which is of interest to many biological assays; and 4) Bumble bees are substantially messier causing potential issues with automated recognition of tags. In 2015, Crall et al. published a camera system for detailed, long term tracking of all bumble bees in a hive [13]. We hope for this system to complement theirs, as a low barrier-of-entry and low-cost alternative for biologists who wish to automate collection of data at the hive entrance; all design files are available at `www.github.com/CEI-lab/BumbleBeeTunnels`.

Specifically, our system captures high-quality, close-up photos at 20 fps of bumble bees as they enter and exit the hive through a single tunnel. Top view photos enable tag identification; side view photos enable recognition of pollen baskets; combined these photos can give a good estimate of the size of the bee. The system measures approximately 20×20 cm, cost less than 300 USD, and takes a few hours to assemble. The electronics are all commercially available and the chassis can be printed on any low-end filament printer. Depending on their comfort level users can use the wireless network interface and use SSH to monitor and download data, or simply by reading the data off of a USB key. The entrance was designed with ample input from and trials with biologists – early versions were tested over 3 weeks with bumble bees foraging in the field, and later versions in a greenhouse over 4 weeks. We have demonstrated its use with unmarked bumble bees, and bumble bees with a variety of tags ranging from AprilTags to honey bee plastic markers. Although the entrance is not well-suited for the very high activity that is characteristic of honey bees, we found that the entrance works well for other species, such as ants.

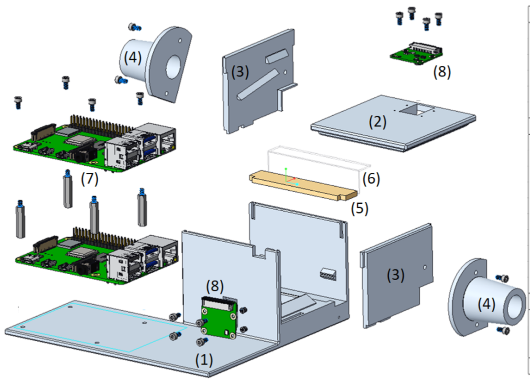
2 Entrance Design and Fabrication

The entrance consists of a base plate that holds the electronics, a tunnel to contain the bees as they enter and exit their hive, and an enclosure around this tunnel that mounts the two cameras and ensures uniform light conditions.

Our first version was made out of laser cut 1/8" wooden panels, with a clear acrylic tunnel. In counsel with biologists, the second version of the entrance was based entirely on 3D printed parts that slot together largely eliminating the need for screws and glue. 3D filament printers have become significantly cheaper and more user friendly over the last few years, and many companies offer quick printing services. Furthermore, PLA (Polylactic acid) material as is most commonly used in low-end printers is also generally recognized as food safe and does not bother the bumble bees.

Our pieces were printed on a Prusa mkII printer with 25% infill and 0.15mm layer height. However, any printer with a minimum print volume of $0.15\times0.16\times0.07m^3$ can be used. The white PLA helps reflect light in the enclosure and provide a high contrast background for images. Support material tend to be what causes novice users the most trouble, both due to suboptimal printer settings and due to the annoyance of post-processing. Therefore, all pieces were specifically designed to require minimal or no support material. The mechanical components needed to build an entrance are shown in Fig. 2. To hook up the entrance to a classic hive box, we designed front and back adapters that fit a 1" flexible tube. Other components include a base, front and back panels which slot into the base and is fastened by the front and back adapter pieces. Finally, a top panel functions as a lid for the enclosure and a mounting spot for the top camera.

The tunnel through which the bees enter and exit have a wooden floor and clear plastic facing the side and top view camera. The wood is 1/8" thick and can easily be cut to size ($75\times18mm^2$) with a box cutter knife, and placed into a designated cavity in the base plate. The clear plastic can be made from any transparent material, but we used 18 mil PETG (Polyethylene terephthalate glycol, a particularly tough polyester thermoplastic). To create the piece, we simply cut a $30\times75mm^2$ rectangle, and scored it down the center to create a rectilinear fold. The piece was then inserted into designated slots in the base and pinched into place securely between the wooden floor and the front and rear panels. Both the wood and the clear plastic pieces were specifically designed



Components	Quantity	Manufacturer	unit price
[1]Base, 133g	1	-	-
[2]Top panel, 30g	1	-	-
[3]Front/back panel, 28g	1	-	-
[4]Front/back adapters, 39g	2	-	-
[5]10x80x3mm wood	1	-	-
[6]10x80x0.8mm transparency	1	-	-
Electronics	**Quantity**	**Manufacturer**	**unit price**
[7]RPi 4, 2GB	2	Raspberrypi.org	61.99 USD
[8]Camera module v2	2	Raspberrypi.org	29.99
RPi 4 3.5A power supply	2	Raspberrypi.org	10.99 USD
RPi 4 dual cooling fan	1	GeeekPi	12.59 USD
RTC (PCF8523)	1	Adafruit	5.95 USD
Ethernet cable, 0.5ft	1	GearIT	1.65 USD
32GB micro-SD card	2	SanDisk	7.96 USD
256GB USB 3.0 key	1	SanDisk	36.99 USD
White LED 3mm	16	Chanzon	0.07 USD
220 Ohm resistor	6	EdgeLec	0.06 USD
Assembly	**Quantity**	**Manufacturer**	**unit price**
M2.5 stand-off, 20mm	8	Heshin	0.21 USD
M2.5 screw, 6mm	8	Heshin	0.07 USD
M2 screw, 6mm	8	Heshin	0.07
Total			287.62 USD

Fig. 2: Left: Exploded view of the entrance; numbers relate to superscripts in the table on the right. The cameras are mounted ∼55mm from the tunnel surface. Note that all components are also available on Amazon, except for the 3D printed pieces produced with PLA at 21.99 USD/kg. For assembly, users need a screwdriver, a box cutter, a needle nose plier, a soldering iron, a screen, and the ability to program the micro-SD cards.

such that they can be removed, cleaned, and/or replaced easily. This is critical, because they get covered in dirt over the span of days.

Bumble bees readily crawl through small spaces in any orientation, and we took several measures to encourage right-side up crawling in the tunnel: 1) we experimented with a range of dimensions; 2) we found that bumble bees prefer walking on the wooden floor over the plastic sides; and 3) we added a small amount of Vaseline near the entry to the tunnel on the walls and ceiling.

3 Electronics

The electronics consist of two stacked RPi 4 embedded computers, each managing a separate camera for increased throughput. The RPis are connected via an Ethernet cable: one board fits a real time clock (RTC) for accurate time stamps, the other powers all enclosure lights and a debugging LED. The software and memory of the RPi is stored on a micro-SD card. Instead of storing images there, we found that biologists preferred a separate USB key for image storage which could be unmounted without accidentally messing with the software. The lower board, which mounts the USB, further has a processor-specific cooling fan. We found that this could be necessary to prevent the RPi from rebooting on exceptionally hot and high activity days in the field.

The most involved assembly step is arguably the enclosure lights. These involve five sets of three LEDs wired in parallel coupled with a current-limiting resistor. These are positioned to create optimal illumination for the bees, and face away from the tunnel to avoid glare in the clear plastic. For consistency, five extrusions in the entrance base, front and rear panels indicate where these LEDs should be glued to. Similar slots ensure that the cameras are mounted correctly with respect to the tunnel. Upon mounting, these camera lenses must be focused. This step requires an external screen and a micro-HDMI cable.

4 Unique Bee IDs

Some experiments call for unique identification of individuals. Towards this goal, we tested both traditional plastic bee tags and several types of paper-based IDs mounted with super glue (Fig. 3). Empirical studies revealed that plastic tags were the easiest to mount and manually read, but could produce glare in images due to their rounded surface. Paper-based tags worked well when printed on high-resolution laser printers and covered in clear tape for water resistance, but had a negative impact on smaller bees due to their size. To automatically process images, we focused especially on the use of AprilTags [14]. The AprilTag library can efficiently identify several tags per image, outputs both their ID and pose, and is robust to a significant noise level (or occluded pixels) which work well with dirty tags. Specifically, we used the 36h11 family which fits hundreds of individuals. The devices support both post- (offboard) and real time- (onboard) processing, and we demonstrated the ability to automatically detect the ID and pose in up to 70% of the captured images. We should note however, that once the tags became too dirty to automatically identify, it was hard to manually post process the images; this led biologists to preferentially use numerical tags.

5 Software and Post-Processing

We optimized the software to detect bees and record images quickly. The image sensor has several operating modes; we used 640x480pxl resolution, which is also the fastest mode. This format is pixel binned, which further enhances sensitivity and allows us to take low-blur images even when the bees move quickly, which eases tag reading. Furthermore, we only store images that contain moving bees. We found that bees or other insects sometimes stay in the tunnel for hours, therefore to avoid excessive recording we incorporated a relatively fast change detector. We first downsample the image to speed up computation and then threshold it aggressively, so that we reliably capture only the dark colored features of the insect. We then sum all the pixel values and keep only frames that are sufficiently different from a computed running average with an exponential decay rate of $\alpha = 0.9$. We tuned the distance and α so that, worst case, the system only takes a few dozen images for large static objects.

Once an image is captured, the biggest bottleneck is the write speed to memory. We wrote the software such that the main task writes images as quickly as possible to a buffer and leaves it to background processes to remove images from

Fig. 3: Photos of different tags taken with the entrance monitor, including binary and numerical on paper and plastic.

the buffer and write them to the file systems. Because the memory is sufficiently big to buffer all images from individual events, we use a single USB key for both RPis. The key is mounted during bootup and exported as a network drive via Ethernet to the other RPi, which then mounts it via the NFS filesystem.

The RPis also exchange the actual time from the RTC. To make the image analysis more portable, we store each image with the system-ID, top/side, and capture time. This means that each collection of images can be analyzed by a variety of programs and that an accidental switching of USB keys is easily fixed. Finally, it is worth noting that the top camera will work even if the side camera is not engaged, meaning that researchers interested only in knowing the activity log of bees could cut the price of the entrance in (roughly) half.

The data captured by the entrance lends itself to a range of automated post-processing. In exploratory work, we use of time stamps to cluster entrance and exit events for rough activity counts (Fig. 4.D), and estimate bumble bees size by first identifying images that capture the entire bee through local thresholds, then achieve relatively good segmentation by subtracting the background image, thresholding each color channel, followed by a speckle reduction filter and ellipsoid fitting (Fig. 4.E). Automated characterization of pollen basket presence, size, and color is an interesting area to pursue in the future.

6 Characterization and Field Tests

Overall, we have assembled and deployed 6 of the entrances (2 first version, 4 second version) and found that the new version can be comfortably replicated and setup in a normal workday. Qualitative feedback from users was positive regarding ease of use and data collection efficiency; with the note that additional protection from the elements would be necessary for field biologists. We tested the first version of the entrance 31/07/19 - 21/08/19 with two hives of the species *Bombus impatiens*, the common eastern bumble bee. The devices and hives were positioned inside of a shed, with holes drilled into the walls to serve as entry and exit points. The temperature for this period spanned 12-34^{o}C, with an average dew point of 12^{o}C. The entrance functioned as expected, with only two brief power-outages causing disruptions in the data collection. Fig. 4.A shows examples of successfully detected bees; Fig. 4.B-C shows examples of outliers ranging from intruders to lost and dirty tags, angled bees, and tandem runs.

The second version of the entrances ran from 9-5pm in a Cornell greenhouse 01/03/21 - 01/04/21 on four active hives, capturing tens of thousands of images. We tested the accuracy of the entrances over two hives for 30 minutes. During this interval we manually counted 69 entries and exits. Cross checking with the entrance, all of these events were captured with legible tags, alongside an additional two events which the manual counter missed. Preliminary analysis of the data file indicates that we capture images with an average frame rate of just above 20 fps, with sizes ranging from 49-74KB. The entry and exit sequences vary greatly in time, producing anywhere from 5 to 72 images per camera with a mean of 21.7. For reference, our most active hives exhibit $\sim$112 events per hour, producing at most 4GB of data per day.

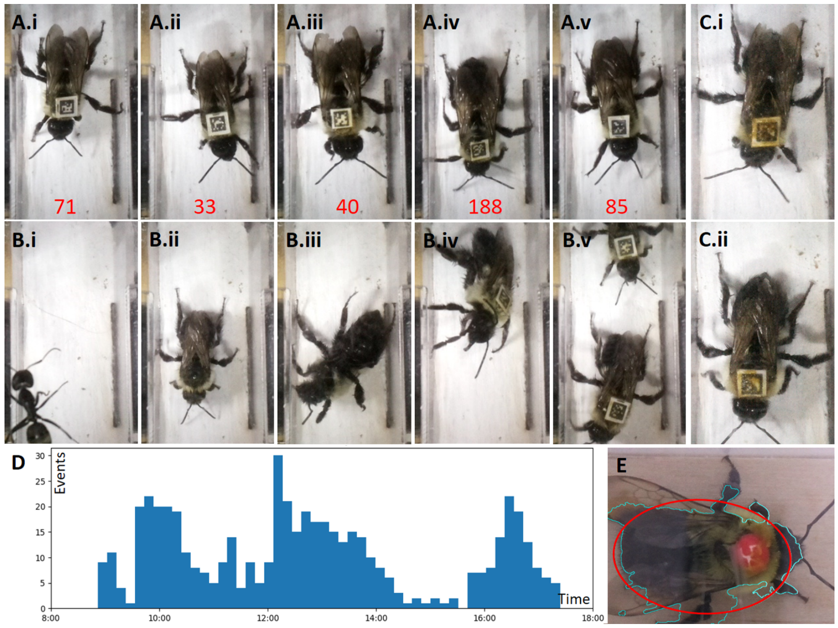


Fig. 4: Sample photos captured with the entrance attached to a Bombus impatiens colony, 08/19. A.i-iv) Bees entering/exiting the hive with correct IDs. B) Scenarios where IDs were more difficult or impossible to identify due to i) foreign visitors, ii) lost tags, iii-iv) angled entries, v) crowded entries. C.i) Example photos in which the tags could not be identified due to dirt. D) Combined entries and exits from 4 hives at the greenhouse (524 events), 17/03/21. E) Individual size analysis based on simple image analysisof photo shown in Fig. 1.C.

7 Discussion

In brief, we presented a new device for automated monitoring of bumble bee entrance activity, with a special focus on accessibility with low cost and simple fabrication and operation. The device facilitates quantitative and qualitative studies on managed bumble bees; insights on which may benefit both entomology and bio-inspired engineering applications. Our device has been extensively tested with real bees and present many opportunities for extension including automated post processing of data to monitor activity levels, individual differentiation, and pollen loads. In the future, we hope to add a load cell to distinguish individual weight gains due to pollen and nectar payloads.

Acknowledgments

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