Flying in a 'bee cloud': Mid-air collision avoidance strategies

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Abstract— **When foraging bees are prevented from re-entering their hive, they fly in a holding pattern near the hive entrance. This scenario, which we term a 'bee cloud', offers an excellent opportunity to investigate how a group of insects (bees) avoid mid-air collisions when flying in close proximity to one another in the vicinity of a landing target (hive). Many researchers have shown that the collision avoidance response in insects is exhibited through turning manoeuvres. In this study, we focus on the factors which influence the turning behaviour of the bees in a cloud. Our preliminary findings suggest that bees turn away from the visual field in which the bees are more numerous and/or closer.**

I. INTRODUCTION

We have been studying collision avoidance behaviours in honeybees by setting up 'bee clouds'. A bee cloud is a test scenario which allows us to investigate how flying insects (bees) avoid mid-air collisions in dense air spaces while loitering in the neighbourhood of a landing target. This scenario is different from the well-studied swarming behaviour, where a group of bees makes a coordinated flight toward a distant goal [1].

In 2012 Groening et al.[2], documented a mid-air collision avoidance strategy used by honeybees. When two bees approach each other head-on at the same altitude, each bee steers to its left, to avoid the head on collision. Interestingly, they do not perform this maneuver when they are flying at different heights. A study of mid-air collision avoidance in Budgerigars [3] found that these birds avoid head on collisions by veering to their right. These strategies - as simple as they might seem - could be used as a starting point to design guidance laws to avoid collisions between aircraft. There is to date relatively little knowledge about how flying insects avoid head on collisions with each other (hence the limited number of cited papers).

We are trying to address the collision avoidance problem by exploring the visuomotor strategies that flying insects use to avoid mid-air collisions by reconstructing the visual experience of each bee flying in a cloud, due to the presence and motion of the neighbouring bees. This will enable us to link the visual experience of the bee to its motor behaviour, instant by instant, to understand the visual cues that mediate the avoidance of collisions. Our preliminary findings so far in this research is presented here.

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II. EXPERIMENTAL SET-UP

A non-captive honeybee (*Apis mellifera*) colony was maintained on a terrace in a semi – outdoor environment. The bees were allowed to forage freely without any restrictions. The experiment was commenced by temporarily blocking the hive entrance with a corflute. The returning foraging bees were thus temporarily denied entry into the hive, but flew near the vicinity of the hive entrance, making multiple attempts to gain access. The resulting 'bee cloud' was filmed using two synchronized digital cameras (Redlake), configured to obtain stereo data. The cameras recorded video at 60 fps, with 500 X 500 pixel resolution.

Before commencing the experiment, stereo camera calibration was performed to obtain the cameras' intrinsic and extrinsic parameters. The video streams acquired by the two cameras were subsequently analysed by digitising the bee's head and tail positions manually in each frame, to obtain the bee's position coordinates in each view. A triangulation routine was executed to obtain the three-dimensional positional coordinates of each bee. The recording duration was 5.8 seconds (349 frames). The frames in the video footage carried varying numbers of bees, as individual bees entered or departed from the fields of view (FOV) of the two cameras. Fig. 1 shows a perspective view of the bee cloud at a particular instant of time.

Fig. 1: A perspective view of the bee cloud.

III. RESULTS & DISCUSSION

The bee cloud data contains 3D position coordinates of a total of 66 bees. To understand the visual cues that mediate the avoidance of collision, we recorded the bee count and inter-bee distances in the visual field of each bee flying in a cloud. For this purpose, the panoramic visual field of a bee was subdivided into 6 pyramidal sectors (enclosed in an imaginary cube) as shown in Fig. 2(a). According to this configuration, if a reference (observer) bee views a neighboring bee in the frontal visual sector, but at a point close to the edge joining the front and right faces of the imaginary cube (frontal right visual sector), the neighbouring bee is classified to be in the frontal visual sector. To classify the locations of the neighboring bees in a more meaningful way during turning flights, the imaginary cube is rotated by 45 deg, as shown in Fig. 2(b). The reference bee's panoramic visual field now comprises a front-right visual sector (F-R), a front-left (F-L), a rear-left (R-L), a rear-right (R-R), a top and a bottom visual sector (VS). This configuration permits a more precise comparison of the numbers and ranges of the bees to the left and the right of the reference bee.

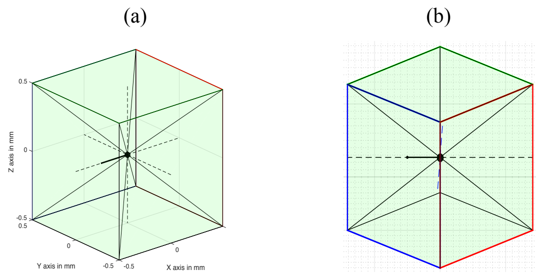

Fig. 2: (a) Panoramic visual field of a bee, subdivided into 6 pyramidal sectors. The observer bee is located at the centre of the cube with its head marked as a black dot, and the body orientation represented by the thick black line. (b) Imaginary cube configuration used for turn correlation analysis. The observer bee is located at the centre with its head marked as a black dot.

A. Correlation of turning behaviour with the visual stimulus

We commenced our analysis by calculating the neighbouring bees' positions in the visual sector of the observer (reference) bee, while the observer bee was executing turning flights. The flight trajectories of bees in the cloud can be subdivided into left turns, right turns and straight flights. The flights were classified as turning flights based on the bee's rotation about its dorsoventral axis. If the rotation about the dorsoventral axis (Z_n) of a bee is in the clockwise direction, then the bee turns to the right, and vice versa.

In order to determine the turning direction, we computed the 3D rotation vector, which is given by the cross product between the unit velocity vector and the unit centripetal acceleration vector. The bee's turning direction is then obtained by taking the dot product of the 3D rotation vector with the unit vector representing the dorsoventral axis of the bee. If this dot product is positive, the bee is turning right; and vice versa. This procedure was used to classify the turning direction. Finally, we imposed curvature magnitude thresholds of 20 to select left and right turns, from the entire flight trajectory for the analysis.

We computed the mean bee counts and the mean ranges of other bees in each visual sector while the observer bee was performing right or left turns. To obtain the mean bee count in each visual sector, we recorded the bee count information in each visual sector of a single observer bee over its particular flight path and then computed the mean count for each visual sector. We then repeated this step for each of the 66 bees. Finally, we computed the overall mean count within each sector, averaged over all 66 bees. The result is shown in Fig. 3, where the bars show the mean bee count within each sector, and the dashed red line shows the global mean count, averaged across all 6 sectors. A similar procedure was used to compute mean range in each visual sector and a global mean range. The plot depicting mean range across all 6 visual sectors is shown in Fig. 4.

From this analysis, we conclude that the bees are trying to maintain an average distance of about 230 mm from their neighbours in each of the six-pyramidal visual sectors during right turns. During left turns, the average inter-bee distance is very similar – 228 mm – and is again approximately the same in each of the six visual sectors.

We expected that any universal behaviour for avoiding collisions would be revealed by the analyses described above. However, ANOVA tests revealed that there were no significant variations in the mean bee counts ($p = 0.319$) or the mean ranges ($p = 0.631$) across the six visual sectors during the right turns. Similarly, the mean bee counts ($p = 0.923$) or the mean ranges ($p = 0.353$) did not vary significantly across all six visual sectors during the left turns as well. Therefore, these analyses did not provide useful information about the visual cues that mediate the turning behaviour. We then started to analyse the turning flights bee by bee, to obtain a better understanding of the factors that control turning behaviour. The results are described in the following section.

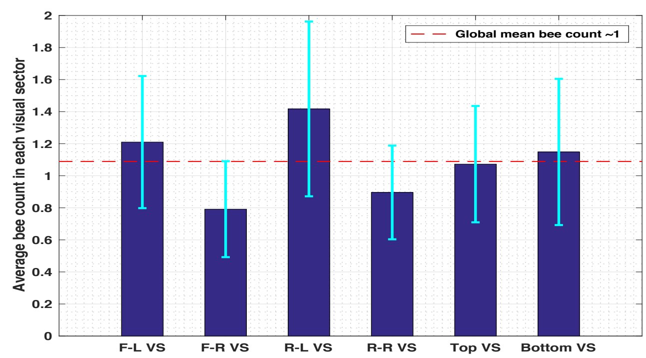

Fig. 3: Mean bee count in each visual sector while executing right turns. Error bars represent the standard error of the mean (SEM).

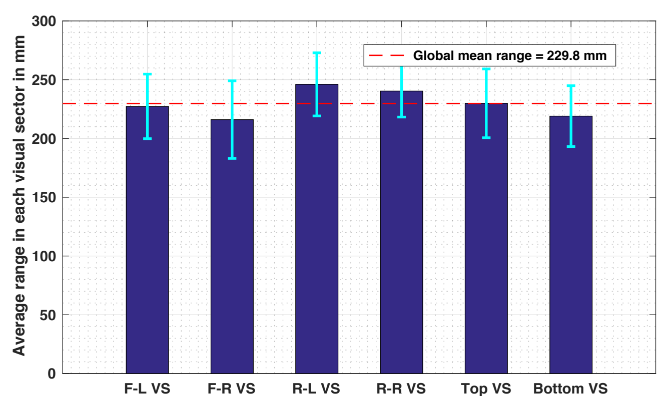

Fig. 4: Mean range of bees in each visual sector while executing right turns. Error bars represent the standard error of the mean (SEM).

B. Turn correlation analysis – individual bees

Here, we investigated for each observer bee, the distributions of the positions and ranges of all other bees when the observer bee was making a turn. As a standard procedure, we extracted the turning parts of the flight by imposing a curvature threshold. If the curvature traced by the observer bee was greater than a particular threshold value (+20) for 5 consecutive frames, this set of five points was considered to constitute a right turn segment. Similarly, if the curvature traced was less than a particular threshold value (-20) for 5 consecutive frames, then a left turn was executed by the observer bee. After visually inspecting the extracted turns, one can categorise them into two different classes: (a) turning flights in the horizontal plane (b) turning flights in the vertical plane. As a first step towards studying the turning behaviour (collision avoidance behaviour), we decided to focus on the turning flight segments only in the horizontal plane. We computed the bee count in the front-right and front-left visual sectors during all horizontal left and right turn segments. In addition to this, the maximum proximity between the observer bee and all other bees in each frame was estimated, to test if the proximity between the bees could be a factor for triggering a turn. Figs. 5-6 show the bee counts and the maximum proximity, respectively, in the front-left and the front-right visual sectors during a horizontal left turn.

Finally, we computed the Integrated Proximity Factor (IPF), which is a combined measure of the number of bees as well as their proximities within a visual field. In other words, the IPF allows us to conveniently measure the joint effect of the bee count and their proximity within a visual field in a single plot. The integrated proximity factor is given by:

$$\text{Integrated Proximity Factor} = \sum_{i=1}^{n} (1 / R_i) \quad (1)$$

Where

R_i - is the range between the observer bee and the i^{th} neighbouring bee.

n - is the number of bees in a particular visual sector.

The IPFs in the front-left and front-right visual sectors, during a horizontal left turn segment of bee number 2, are shown in Fig. 7. It is evident from Fig. 5 that the bee count in the front-right visual sector is higher than that in the front-left visual sector. This suggests that the observer bee is turning away from the visual field in which more bees are present. Secondly, we note that the maximum proximity is more or less the same in the front left and right visual sectors. A joint measure of bee count and proximities in the visual sectors have resulted in a high IPF in the front-right visual sector during a left turn, as shown in Fig. 7.

On the basis of the above findings, we predicted that right turns are triggered by (i) a greater bee count and (ii) a greater proximity of bees, in the front-left visual sector. Thus, one would expect a higher IPF in the front-left visual sector during a right turn, and in the front-right sector during a left turn. We tested this prediction by analysing the horizontal left and right turns of each bee. So far, we have analysed 38 out of a total of 42 bee flights, comprising numerous extracted turn segments (using a threshold curvature magnitude of 20 to define a turn), to test which of the criteria discussed above could be responsible for initiating the turns (24 flights were removed from the analysis since they did not satisfy the applied constraints).

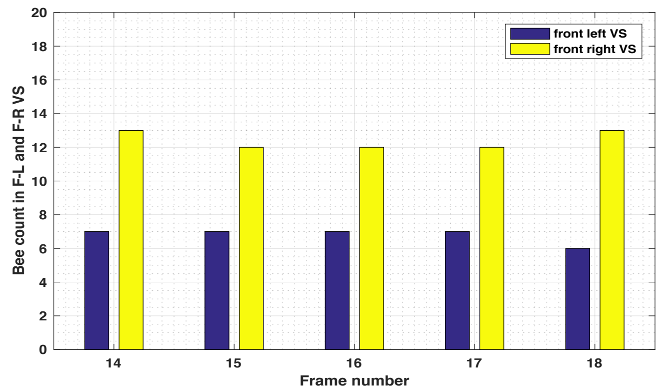

Fig. 5: Counts of bees in the front-left and front-right visual sectors between frames 14 and 18, during a horizontal left turn segment.

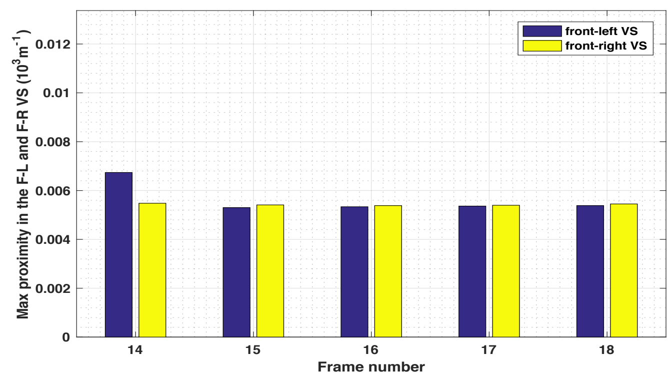

Fig. 6: Maximum proximity between the bees in the front-left and front-right visual sectors between frames 14 and 18, during the same horizontal left turn segment as in Fig. 5.

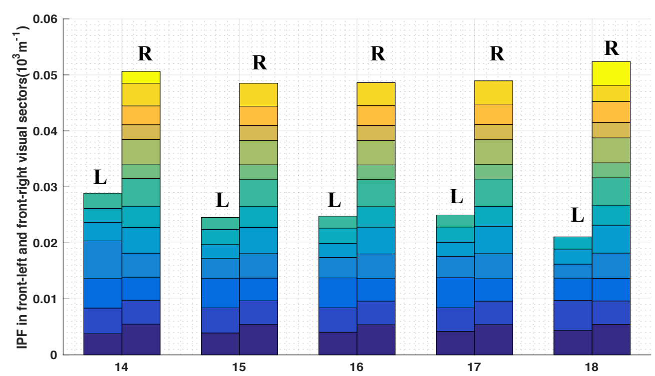

Fig. 7: Integrated proximity factor (IPF) in the front-left and front-right visual sectors between frames 14 and 18, during the same horizontal left turn segment as in Fig. 5. L and R denote the front-left and the front-right visual sector, respectively. The different colors of the stacked bar chart are used to differentiate proximities of individual bees within that visual sector.

We assessed the accuracy of our predictions (in %) by calculating the number of times the predictions were correct for the left runs and the right turns. The results are shown in Table I. For the left turns, the IPF is the best predictor; for the right turns, the IPF and the bee count are equally reliable.

TABLE I. PREDICTION ACCURACY FOR LEFT & RIGHT TURN SEGMENTS

Turn Direction	Bee count	IPF	Max Proximity
Left	61%	70%	66%
Right	54%	54%	46%

Interestingly, each of the criteria examined predict the left turns more reliably than the right turns. The reason(s) for this remain to be explored. One possibility may be that this bias is related in some way to the head-on collision avoidance maneuvers of honeybees, where each bee tends to veer to its left. Another explanation may be a preference for bees to use one eye preferentially to view conspecifics, as has been reported for many animals (e.g. [4]). Further work is required to examine these and other explanations for the apparent bias.

IV. CONCLUSION AND FUTURE WORK

Our study so far suggests that bees flying in a cloud (under our experimental conditions) maintain a mean separation of about 230 mm in all directions, and a mean count of about one bee for each of the six visual sectors. This is suggestive of an effective collision avoidance strategy. Indeed, we have not observed a single collision in our data set. Collisions may be avoided by turning away from the region of the visual field in which the bees are greater in number, or closer in range.

Future work will involve (a) examining whether the turning behaviour of the reference bee is influenced by the optic flow that generated by the relative movement of the neighbouring bees in its visual field; and (b) investigating the visual cues that control the instantaneous flight speed of individual bees flying in the cloud.

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